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User Needs, Benefits, and Integration of Robotic Systems in a Space Station Laboratory

Final Report

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Teledyne Brown Engineering
Huntsville, Alabama

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16. Abstract

This Final Report for the National Aeronautics and Space Administration/Lewis Research Center (NASA/LeRC) summarizes the methodology, results and conclusions of all Tasks of the User Needs, Benefits, and Integration Study (UNBIS) of Robotic Systems in a Space Station Laboratory. Study goals included the determination of user requirements for robotics within the Space Station, United States Laboratory. In Task I, three experiments were selected to determine user needs and to allow detailed investigation of microgravity requirements. In Task II, a NASTRAN analysis of Space Station response to robotic disturbances, and acceleration measurement of a standard industrial robot (Intelledex Model 660) resulted in selection of two ranges of microgravity manipulation: Level I (10-3 to 10-5 G at >1Hz) and Level II (<=10-6 G at 0.1 Hz). This task included an evaluation of microstepping methods for controlling stepper motors and concluded that an industrial robot actuator can perform milli-G motion without modification. Relative merits of end-effectors and manipulators were studied in Task III in order to determine their ability to perform a range of tasks related to the three microgravity experiments. An Effectivity Rating was established for evaluating these robotic system capabilities. Preliminary interface requirements for an orbital flight demonstration were determined in Task IV. Task V assessed the impact of robotics.

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SUMMARY

The purpose of this study is to identify and define the potential for robot application within a low-gravity orbiting laboratory. During Space Station Phase B studies, it was confirmed that extensive amounts of crew time will be required to sustain long duration experiments. Additionally, some experiments require a very low level of gravitational disturbance and others use facilities and materials that are potentially hazardous to the crew.

These findings indicated a very real and significant potential for solution by robotic application in that robotics can be used to perform routine and boring housekeeping tasks; perform tediously repetitive tasks and handle potentially hazardous materials away from the crew; and perform backup for cleanup, salvage, and contingency operations. Our findings point to further emphasis on the importance of automation and robotics to support the crew in achieving a very wide range of goals.

The current study focused on the identification of user needs and benefits for robotic systems in a Space Station laboratory. This was accomplished by defining the steps of typical experiments and then determining how robotic systems might perform these activities. Necessary hardware was defined in terms of dexterity and gravitational disturbance levels. Expected hardware costs were then derived to provide information for a trade study of various robotic system configurations.

The anticipated Space Station configurations were analyzed to compare potential robot system disturbances with other potential external disturbances [such as docking, Mobile Remote Manipulator System (MRMS) operations, Orbital Maneuvering Vehicle (OMV) maneuvers, etc.]. The station long truss structure and mass configuration result in a low resonance frequency (< 1 Hz) and damping factors tend to convert impulsive inputs into long duration low frequency disturbances. Results of the analyses indicate that space station acceleration levels of $10E^{-4}$ to $10E^{-5}$ g below 1 Hz are the only reasonable expectations. This is above the level of $10E^{-6}$ g most experiments requested.

During the course of the disturbance level study [using both Linear Variable Differential Transformer (LVDT) motion sensors and Accelerometers], it

became apparent that the average human performing manual (dexterous) tasks can control acceleration only in the deca milli-g range (10-40 mg) at best, whereas off-the-shelf robotics devices can perform within the milli-g range (1-10 mg). Robotics then can amplify the human ability to minimize disturbance levels. It is expected that further development of robotics technology and design focused on minimizing reactive forces (rather than repetitive speed - the design goal in most of modern industry) can bring robotics disturbance levels to a much lower level.

The costs of single space station robot configurations evaluated are estimated to range from $2M for the least complex single manipulator with simple two finger end effector to $20M for a configuration of dual manipulator arms with dexterous end-effectors.

These estimates include ground teleoperation station, software, and onboard dedicated safety computer. These costs are justified by the larger number of repetitive experiment runs obtainable by robotics for limited amounts of other resources.

Based on the relatively low cost, when measured against its ability to pay for itself by increased production within the first 90-day mission, it is advisable to provide the maximum-capability system. This is further justified by a survey of personnel with backgrounds in robotics and/or flight systems development, where performance was identified as the key weighting factor (44 percent) in comparison with resource consumption (31 percent) and cost (25 percent).

Interfacing the robot with the proposed space station laboratory involves structural, mechanical, data communications and storage, video, and power requirements. These requirements are well within the bounds of current designs except that a segmented rail is required to be added to allow robot access to the laboratory. This can be done without inhibiting access to storage or experiments or significantly affecting current rack designs. However, the decision for scarring for robotic station interfacing should be imposed before PDR.

Numerous aspects of low-gravity robotics have been identified for further attention. Study, research, and development should be accomplished concerning motor and drive techniques and structural and robotic joint design, as well as measurements and control techniques needed to maintain a low gravitational environment.

Finally, and of immediate importance to the Space Station program, development of a flight demonstration robot experiment should be initiated to verify low gravity operational performance characteristics as well as to demonstrate state-of-the-art robotic capability.

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1. INTRODUCTION

The Final Report covers work performed by Teledyne Brown Engineering's (TBE) Space Programs Division between October 1987 and October 1989 for Lewis Research Center (LeRC) under contract number NAS3-25278, Study of User Needs, Benefits, and Integration for Robotic Systems (UNBIS), in a Microgravity and Materials Processing Facility (MMPF).

1.1 UNBIS STUDY BACKGROUND, SCOPE, AND PROCEDURES

Space Station Phase B studies, from 1985 through 1987, indicated a shortage of crewtime based on proposed experiment operations and requirements for space station operations. There was also a user requirement to perform experiments and handle materials (sometimes hazardous) within a "microgravity" environment. This study was directed to provide information on the space station experimenter community's needs for low-gravity manipulation and to evaluate the fiscal and functional impacts of providing that capability.

The purpose of this study is to provide a better understanding of experiment manipulation and dexterity requirements with concurrent acceleration environment requirements on board an orbiting low-gravity laboratory. The study effort was composed of seven tasks, as shown in Figure 1-1.

Task I required the definition of experimenter's needs. These data were defined for 10 typical experiments in terms of operational flow, acceleration limits, manipulation requirements, timing, and potential for disturbances to other experiments.

Task II selected 3 of the 10 experiments for further evaluation. The analysis of disturbance was based on a NASTRAN model of the space station with robotic and outside disturbance sources added for composite analysis. Laboratory acceleration measurement of typical robotic motions was a part of this task.

Task III included costing the various robotic configurations studied and included a review of benefits of each configuration, using the Payload Production and Planning (PAYPLAN) computer program developed by TBE in 1986.

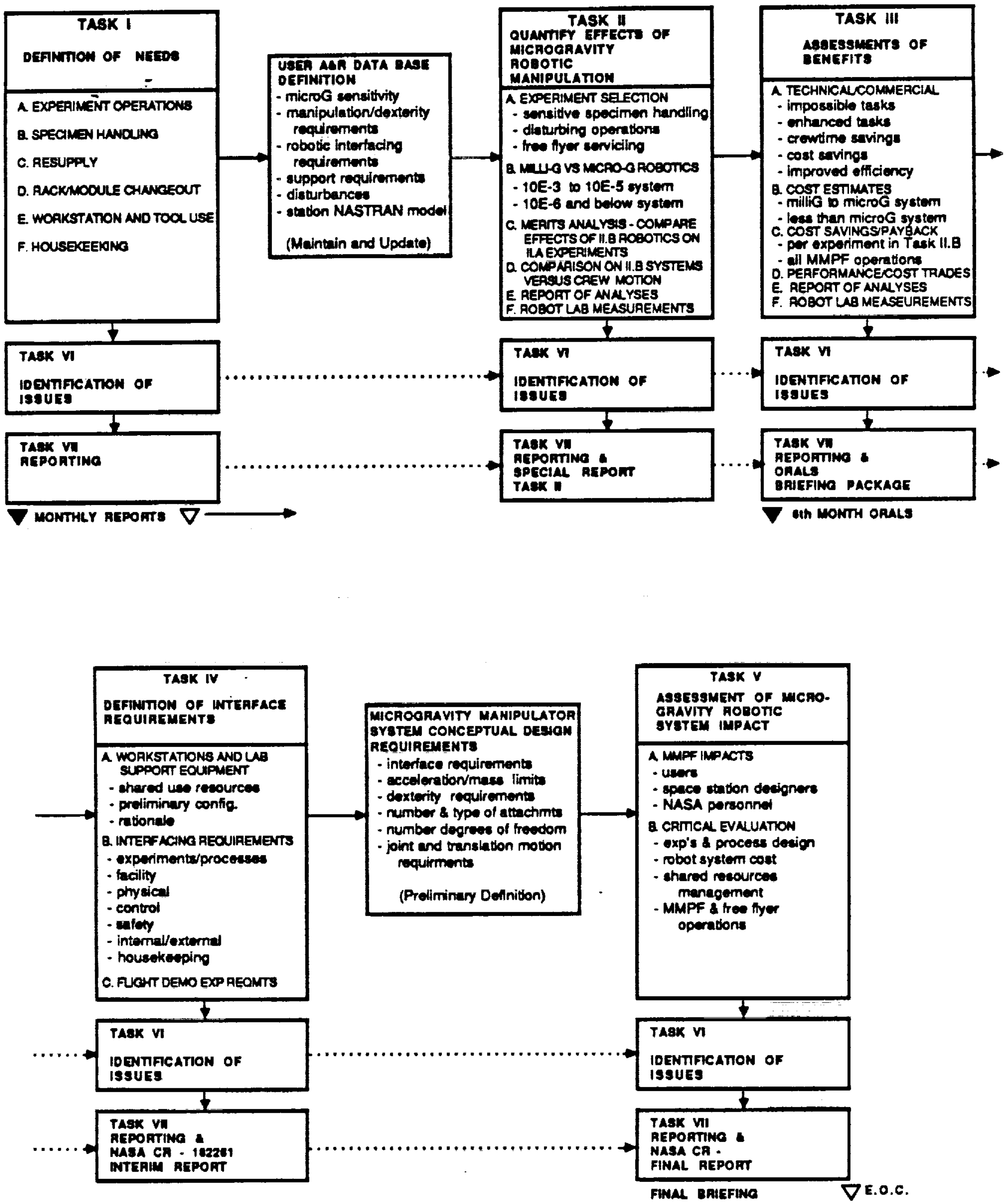

FIGURE 1-1. UNBIS STUDY COMPONENTS

Task IV required definition of interface requirements between the potential low-gravity robotic system and laboratory facilities and experimenters, and included preliminary identification of requirements for a flight demonstration experiment.

Task V provides an evaluation of robotic system impacts to the various affected parties.

Task VI and VII include identification of key issues and reporting concurrently with all tasks of this study.

The procedure included development of the LeRC low-gravity robotics data base from the Microgravity Materials Processing Facility data base as a starting point with the addition of acceleration requirements at each step. The PAYPLAN computer simulation was used to perform part of the benefits assessment.

The analyses of disturbances and reaction effects were accomplished using NASTRAN on a VAX computer by a dynamist.

The TBE Robotics Laboratory industrial manipulator was instrumented and used for the purpose of performing the Task II accelerometer measurements. An Interim Report (NASA CR182261) covered in detail Tasks I through IV-A. This Final Report (NASA CR185150) reviews and updates this material and adds Task IV-B through VI details as well as additional conclusions.

1.2 CONCURRENT STUDIES AND DEVELOPMENT ACTIVITIES

The Flight Telerobotic Servicer (FTS) contracts are concurrent to this study and focus on external operation requirements. International partners including Canada, National Space Development Agency (NASDA), and European Space Agency (ESA) are also pursuing robotic developments applicable to Space Station Freedom operations. All of these impact the low-gravity environment as the reaction from movement of manipulated masses transfer to the station. Additionally, valuable crew time is required to operate these telerobotically.

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2. SPACE STATION USERS REQUIREMENTS

The two primary goals of this study were to (1) define the experiment operations in detail and (2) identify how robotic systems might achieve these operations with a beneficial impact (i.e., lower gravitational disturbance and reduction in crew resources required).

2.1 USER NEEDS DATA BASE AND LOW-GRAVITY REQUIREMENTS

The materials processing community has the greatest need for a low-gravity environment in which to operate their experiments and processes. These requirements are defined in the MMPF Study and Data base. This data base presents a step-by-step definition of processing requirements in terms of resources needed and processing environment specification. Data inputs from over 90 different organizations provided the data to the MMPF which in turn was enhanced with low-gravity levels required and manipulation information (coordinates, traverse distance, and timing requirements).

One conclusion of the MMPF Microgravity Workshop Proceedings was that just being in orbit does not guarantee a disturbance-free environment (with respect to acceleration). Because of their impact to the low frequency, low-gravity acceleration environment, the external disturbances caused by atmospheric drag, gravity gradient, and attitude of the station are of serious concern to materials processing. Larger disturbances are expected from day-to-day operations including both internal and external operations. Theoretical experiment sensitivities and past flight acceleration measurements, along with envelopes of robotic effects to be discussed later, are shown in Figure 2-1. The lower frequency disturbances are not as well tolerated as higher frequency ones, and compounding the problem is the fact that impulse loads are converted to drive the lower resonant frequency of the station.

2.2 ROBOTIC FUNCTIONS TO SUPPORT EXPERIMENT AND HOUSE-KEEPING OPERATIONS

During data base development, it was important to identify all functions during operation of the experiment. Sample processing and manipulation was analyzed from a view to automate each step where possible. An example list of functions along with manipulation requirements is shown in

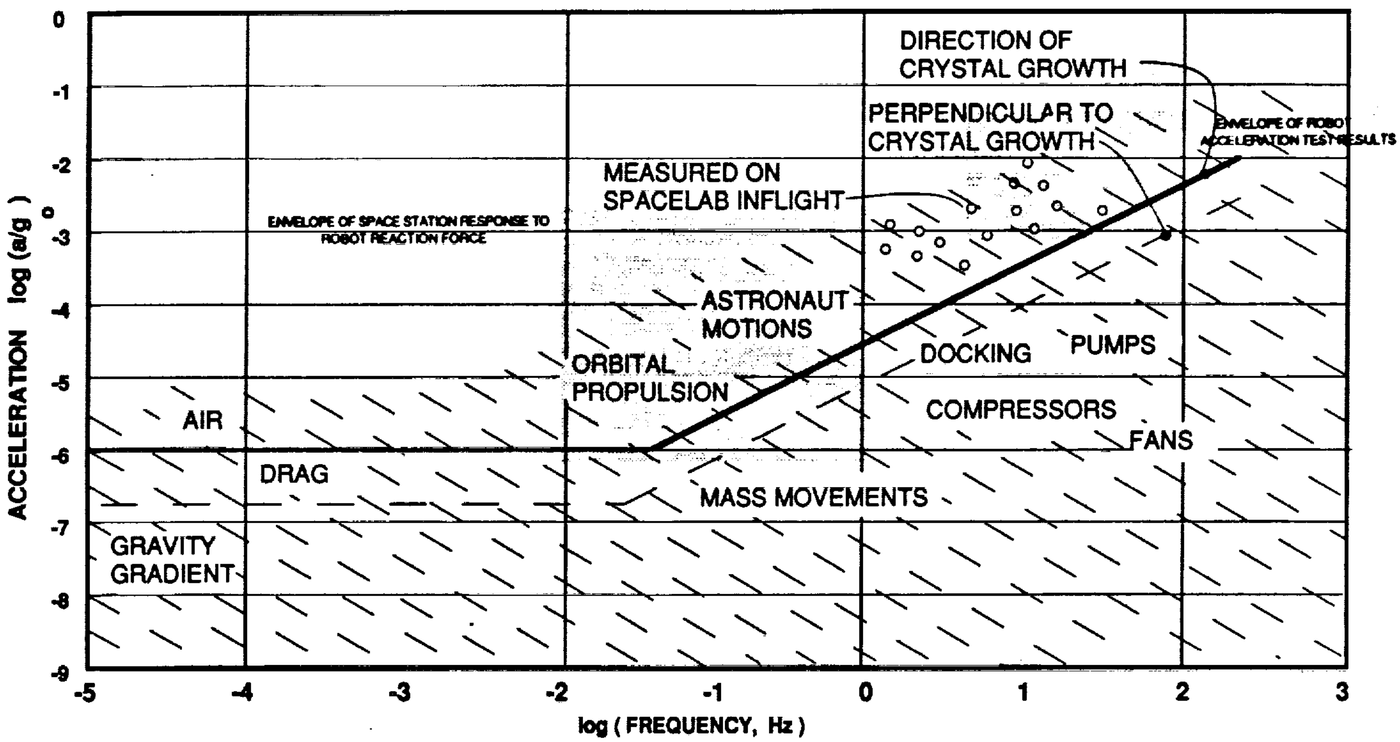

FIGURE 2-1. MICROGRAVITY ACCELERATION SENSITIVITY OF PROCESSES WITH SUPERIMPOSED ROBOTICS EFFECTS

Table 2-1 for a Large Bridgman Furnace facility. This illustrates typical results following the analysis of detailed MMPF timelines. Additional functions were organized as experiment module changeout, facility rack changeout, facility housekeeping, laboratory support equipment (glovebox, microscope, camera storage locker, etc.) usage and non-experiment-specific support.

Robot functions were reviewed by level of required dexterity and control complexity as well as mass, speed, repeatability, reliability, frequency of performance, and shared resources. Capability to perform the required function was based on state-of-the-art and conventional technologies.

Both experiment-specific and housekeeping support (for the range of experiments) were analyzed.

TABLE 2-1. EXAMPLE MANIPULATION REQUIREMENTS AND ROBOTIC ASSESSMENT (Sheet 1 of 2)

STEP NO.	STEP NAME	FACILITY	g-LEVEL		ONE-HANDED ROBOT			TWO-HANDED ROBOT	
			Micro-g	Milli-g	2-Finger	3-Finger	Dexterous	2+3 Finger	2 Fing/ Dext
1.0	Ground to station activities	Bridgman, large	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1.1	Prepare samples	Bridgman, large	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1.1.1	Prepare samples	Bridgman, large	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1.1.2	Load and seal ampoules	Bridgman, large	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1.2	Transport samples and unique equip. to Space Station	Bridgman, large	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1.2.1	Load samples into shipping containers	Bridgman, large	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1.2.2	Load facil. and unique equip. into containers	Bridgman, large	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1.2.3	Integrate containers into logistics module	Bridgman, large	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1.2.4	Transport logistics module to Space Station	Bridgman, large	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1.2.5	Store samples and facility at Space Station	Bridgman, large	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.0	Station integration	Bridgman, large	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.1	Install facility	Bridgman, large	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.1.1	Interface facility rack to lab	Bridgman, large	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.1.2	Install unique equipment in facility racks	Bridgman, large	N/A	N/A	N/A	N/A	N/A	N/A	N/A
3.0	Run preparation	Bridgman, large	N/A	N/A	N/A	N/A	N/A	N/A	N/A
3.1	Prepare for run	Bridgman, large	N/A - Ground	N/A - Ground	N/A	N/A	N/A	N/A	N/A
3.1.1	Review experimental procedures	Bridgman, large	N/A - Ground	Ground	N/A	N/A	N/A	N/A	N/A
3.1.2	Load furnace	Bridgman, large	X	X	•	X	X	X	X
3.1.3	Seal furnace	Bridgman, large	X	X	X	X	X	X	X
3.2	Verify system	Bridgman, large	N/A - Ground	N/A	N/A	N/A	N/A	N/A	N/A
3.2.1	Check all connections and seals	Bridgman, large	X	X	N/A	N/A	N/A	N/A	N/A
3.2.2	Power up processor facility	Bridgman, large	N/A - Ground	X	X	X	X	X	X
3.2.3	Run master controller system test program	Bridgman, large	N/A - Ground	X	X	X	X	X	X
4.0	Run	Bridgman, large	N/A	N/A	N/A	N/A	N/A	N/A	N/A
4.1	Run process	Bridgman, large	X	X	N/A	N/A	N/A	N/A	N/A
4.1.1	Input processing parameters	Bridgman, large	X - Ground	X	N/A	N/A	N/A	N/A	N/A
4.1.2	Furnace and sample heatup	Bridgman, large	X	X	N/A	N/A	N/A	N/A	N/A
4.1.3	Sample soak	Bridgman, large	X	X	N/A	N/A	N/A	N/A	N/A
4.1.4	Crystal Growth	Bridgman, large	-	X	N/A	N/A	N/A	N/A	N/A
4.1.5	Cooldown of furnace	Bridgman, large	X	X	N/A	N/A	N/A	N/A	N/A
4.2	End run	Bridgman, large	N/A	N/A	N/A	N/A	N/A	N/A	N/A
4.2.1	Disassemble furnace as required to remove module	Bridgman, large	X	X	X	X	X	X	X
4.2.2	Remove ampoule from heater module	Bridgman, large	X	X	•	X	X	X	X
4.2.3	Power down controller	Bridgman, large	X	X	X	X	X	X	X
5.0	IOC level characterization	Bridgman, large	N/A	N/A	N/A	N/A	N/A	N/A	N/A
5.1	Analyze product	Bridgman, large	N/A	N/A	N/A	N/A	N/A	N/A	N/A
5.1.1	Photograph boule through	Bridgman, large	X	X	•	•	X	X	X
	wall of ampoule	Bridgman, large	X	X	X	X	X	X	X

TABLE 2-1. EXAMPLE MANIPULATION REQUIREMENTS AND ROBOTIC ASSESSMENT (Sheet 2 of 2)

STEP NO.	STEP NAME	FACILITY	g-LEVEL		ONE-HANDED ROBOT			TWO-HANDED ROBOT	
			Micro-g	Milli-g	2-Finger	3-Finger	Dexterous	2+3 Finger	2 Fing/ Dext
5.1.2	Remove boule from ampoule	Bridgman, large	X	X	X	X	X	X	X
5.1.3	Etch growth reside from product	Bridgman, large	X	X	X	X			
5.1.4	Photograph product	Bridgman, large	X	X	*	*	X	X	X
5.1.5	Measure mass of boule	Bridgman, large	-	X	N/A	N/A	N/A	N/A	N/A
5.1.6	Measure physical dimensions of boule	Bridgman, large	X	X	*	*	*	X	X
5.1.7	Slice sample wafer from boule	Bridgman, large	X	X	N/A	N/A	N/A	N/A	N/A
5.1.8	Photograph wafers	Bridgman, large	X	X	*	*	X	X	X
5.1.9	Polish wafers	Bridgman, large	X	X	N/A	N/A	N/A	N/A	N/A
5.1.10	View and photograph wafer using microscope system	Bridgman, large	X	X	*	*	X	X	X
5.1.11	Etch wafer	Bridgman, large	X	X	X	X	X	X	X
5.1.12	View and photograph wafer using microscope system	Bridgman, large	X	X	*	*	X	X	X
5.1.13	Repeat 5.1.11 and 5.1.12 as required (2x)	Bridgman, large	X	X	X	X	X	X	X
5.2	Characterize wafer crystal structure	Bridgman, large	N/A	N/A	N/A	N/A	N/A	N/A	N/A
5.2.1	Analyze wafer using x-ray system (topography)	Bridgman, large	X	X	X	X	X	X	X
.2	Analyze wafer w/an electrical conductivity probe	Bridgman, large	X	X	X	X	X	X	X
0	Growth characterization	Bridgman, large	N/A	N/A	N/A	N/A	N/A	N/A	N/A
.1	Analyze wafer using FTIR	Bridgman, large	X	X	X	X	X	X	X
..2	Analyze wafer using a Hall probe	Bridgman, large	X	X	X	X	X	X	X
7.0	Analysis	Bridgman, large	N/A	N/A	N/A	N/A	N/A	N/A	N/A
7.1	Package and store products	Bridgman, large	N/A	N/A	-	-	-	X	X
7.2	Perform post-experiment data analysis	Bridgman, large	N/A - Ground	N/A - Ground	N/A	N/A	N/A	N/A	N/A
7.2.1	Reduce data as required	Bridgman, large	N/A - Ground	N/A - Ground	N/A	N/A	N/A	N/A	N/A
7.2.2	Correlate experimental parameters to results	Bridgman, large	N/A - Ground	N/A - Ground	N/A	N/A	N/A	N/A	N/A
7.2.3	Select next run parameters	Bridgman, large	N/A - Ground	N/A - Ground	N/A	N/A	N/A	N/A	N/A
8.0	Clean equipment	Bridgman, large	N/A	N/A	N/A	N/A	N/A	N/A	N/A
8.1	Clean equipment as needed	Bridgman, large	N/A	N/A	*	*	X	X	X
8.2	Stow equipment as needed	Bridgman, large	N/A	N/A	*	*	X	X	X

NOTE: * means that this operation is doubtful with the manipulator indicated. Would require external brace or holding device to assist.

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3. SUMMARY OF LOW-GRAVITY MANIPULATION RESULTS

During the course of this study, numerous experiments were examined to determine the requirements for a low-gravity environment and/or manipulation. Part of the accomplishment of this task involved the study of known and proposed experiments. Ten experiments were selected from the Microgravity and Materials Processing Facility (MMPF) data base developed by the advanced programs group of Teledyne Brown Engineering. This data base contains physical, operational, and environmental characteristics of more than 200 experiments. These experiments are real and proposed facilities that are expected to fly on board the Space Shuttle and/or Space Station Freedom. See Table 3-1 for a list of the initial 10 experiments selected in this study.

TABLE 3-1. INITIAL LIST OF 10 EXPERIMENTS

Acoustic Levitator	Float Zone Crystal Growth
Alloy Solidification Furnace	Fluid Physics Facility *
Atmospheric Microphysics	Large Bridgman Facility *
Continuous Flow Electrophoresis	Protein Crystal Growth *
Droplet/Spray Combustion	Vapor Crystal Growth Facility

* = One of final three selected for further study.

Appendix A contains detailed descriptions of all 10 facilities.

3.1 EXPERIMENT SELECTION AND LOW-GRAVITY REQUIREMENTS

The facilities denoted with an asterisk in Table 3-1 are those that were selected for further study. These three, Large Bridgman Furnace, Protein Crystal Growth (PCG), and Fluid Physics were selected because they each have significantly different microgravity-sensitive operational parameters.

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3.1.1 Large Bridgman Furnace

The Large Bridgman Furnace is a high temperature facility designed for materials processing. It is a very large facility and has a massive front panel/door assembly. This facility is microgravity sensitive during sample processing, and the massive door motion during opening and closing for sample changeout could potentially impart disturbances into the laboratory.

3.1.2 Fluid Physics Facility

The Fluid Physics Facility was selected because it has a different set of microgravity requirements. This facility is sensitive to microgravity immediately before and during processing. The samples processed are liquids that must be "free floated" within the processing chamber. The behavior of the fluid in microgravity is studied with various disturbance inputs. The working fluids are changed, and the characteristics studied are varied depending on the composition of the material. The sample cannot touch the sides of the processing chamber during the experiment. The nature of the experiment and the restriction of facility motions during processing made this an appropriate facility for further study.

3.1.3 Protein Crystal Growth Facility

The Protein Crystal Growth Facility is sensitive to the microgravity environment both during and after processing. Protein crystals have use in the medical field in the treatment of cancer and other areas. The crystals grown on-orbit are larger than those possible in Earth-based laboratories, and are extremely fragile after growth. Many of the crystals grown on Space Shuttle flights to date have succumbed to the movements of the crew and have been destroyed or dissolved. Thus, the microgravity sensitivity for this experiment facility exists both during and after processing.

3.2 ACCELEROMETER MEASUREMENTS AND REACTION FORCE ANALYSES

There are two disturbance categories to be addressed by any microgravity-compatible robot system:

- Direct end-effector manipulation without disturbing the experiment or sample
- Manipulation or motion without transferring disturbances through the robotic base

3.2.1 Robot and Human Acceleration

After identifying the three facilities and their microgravity requirements, several low acceleration level tests were performed to quantify the effect of the first category. The test setups used are depicted in Figures 3-1 and 3-2. These figures represent the configuration of an Intelledex 660 robot as instrumented for measurement of very small motions. The motions commanded were for one microstep (1/1,250,000 revolution). This represents the finest resolution the controller is able to command. However, the encoders on the individual motors have only a 200,000 step resolution. Thus, the encoder would "save up" several command pulses and send a 1/200,000 motion command after receiving enough 1/1,250,000 commands to indicate an error between desired (commanded) and actual positions.

The results indicate that it is possible to obtain 10 E^{-3} g levels of motion with a standard off-the-shelf industrial robotic system (see Figures 3-3 and 3-4). Figure 2-1 shown previously plots the envelope resulting from these robot acceleration tests on top of acceleration requirements. Note that a portion of the envelope falls below the minimum sensitivity threshold. Appendix B contains a more detailed description of these tests.

During the same time period tests were performed using several human subjects to determine the nominal human performance. The test subjects held an accelerometer in their hand between the forefinger and thumb. The forearm and edge of the hand were rested on the table and the intent was to remain motionless. Some of the test results are presented below as Figure 3-5. The general result was that the test subjects revealed a 10 to 20 milli-g level while attempting to remain motionless.

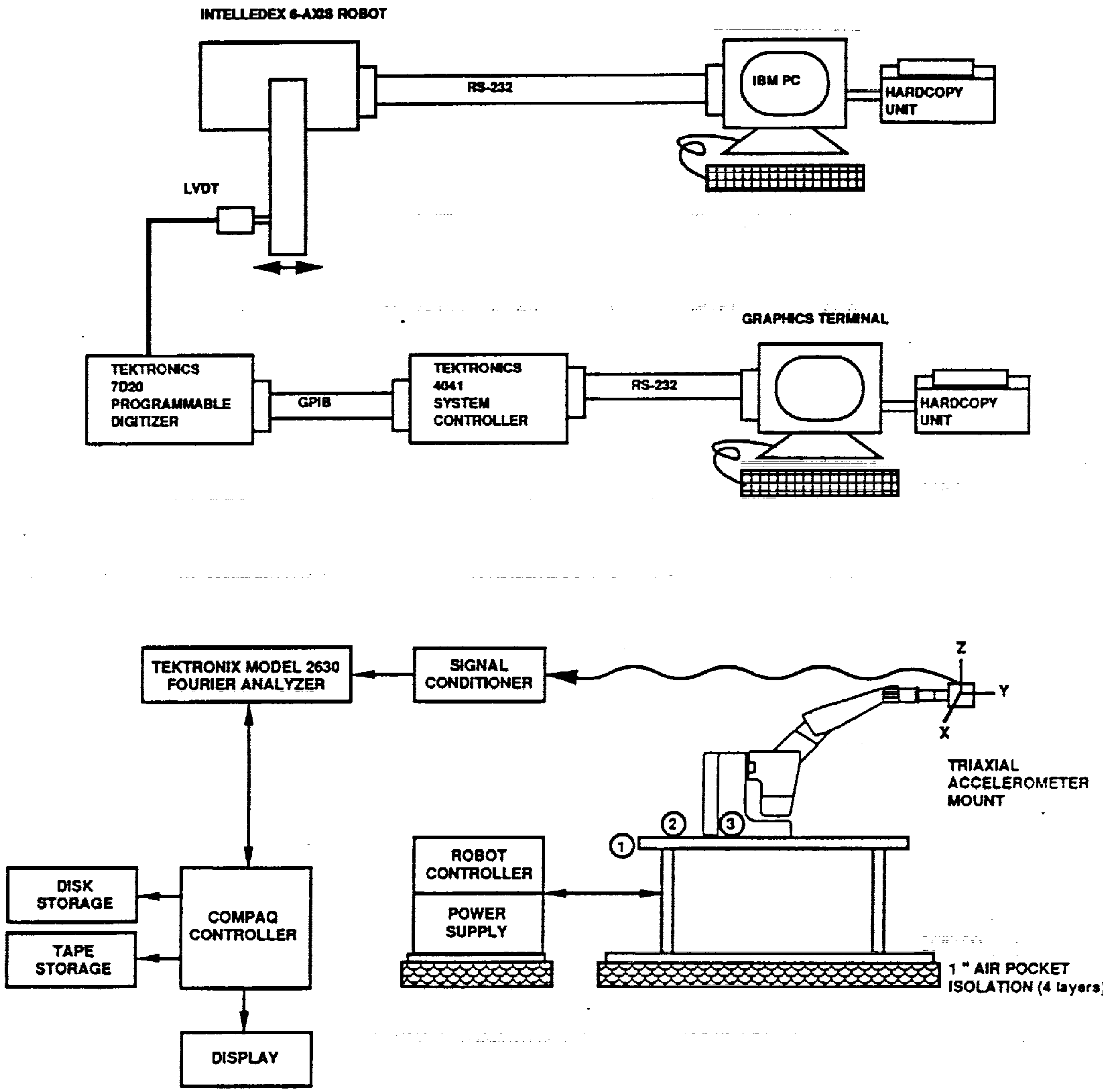

FIGURE 3-1. SETUPS FOR LVDT (TOP) AND QA-2000 ACCELEROMETER (BOTTOM) MEASUREMENTS OF MANIPULATOR MICROSTEPPING

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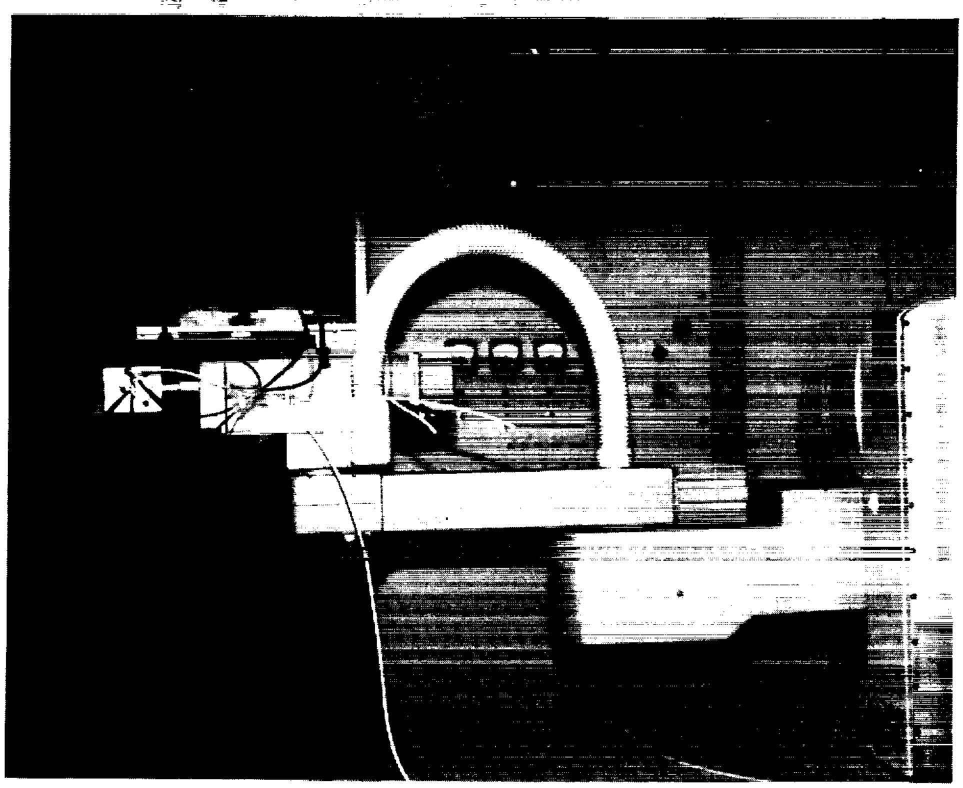

FIGURE 3-2. END-EFFECTOR ACCELEROMETER MEASUREMENT SETUP

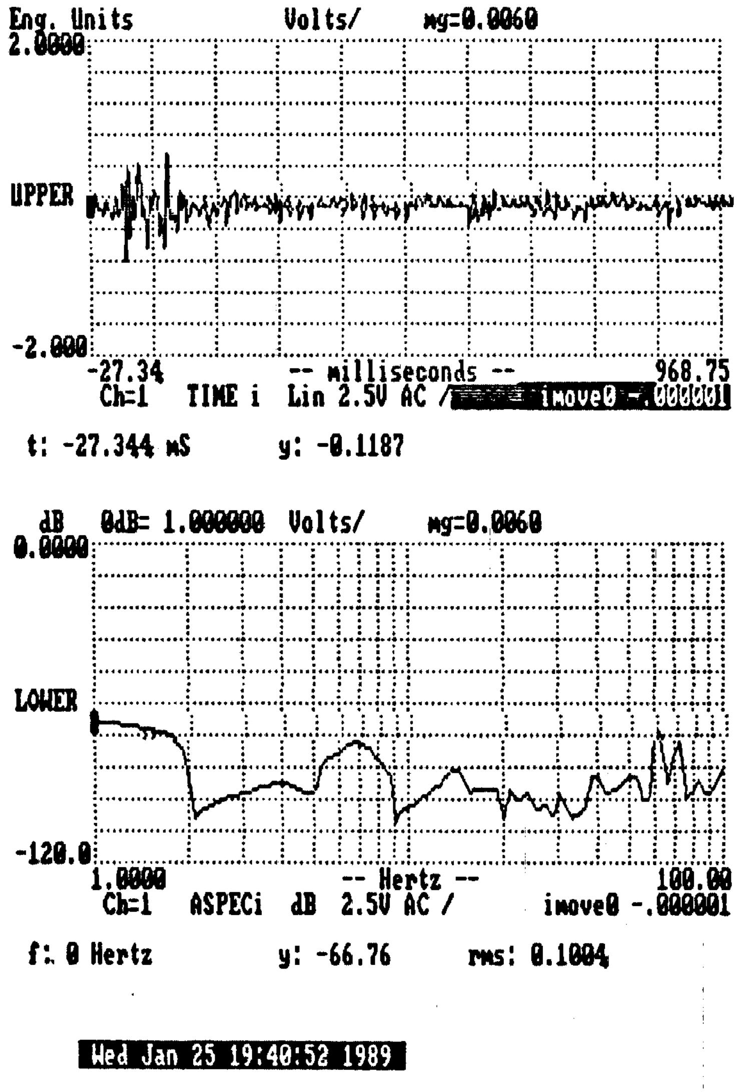

FIGURE 3-3. MICROSTEP ACCELEROMETER MEASUREMENTS

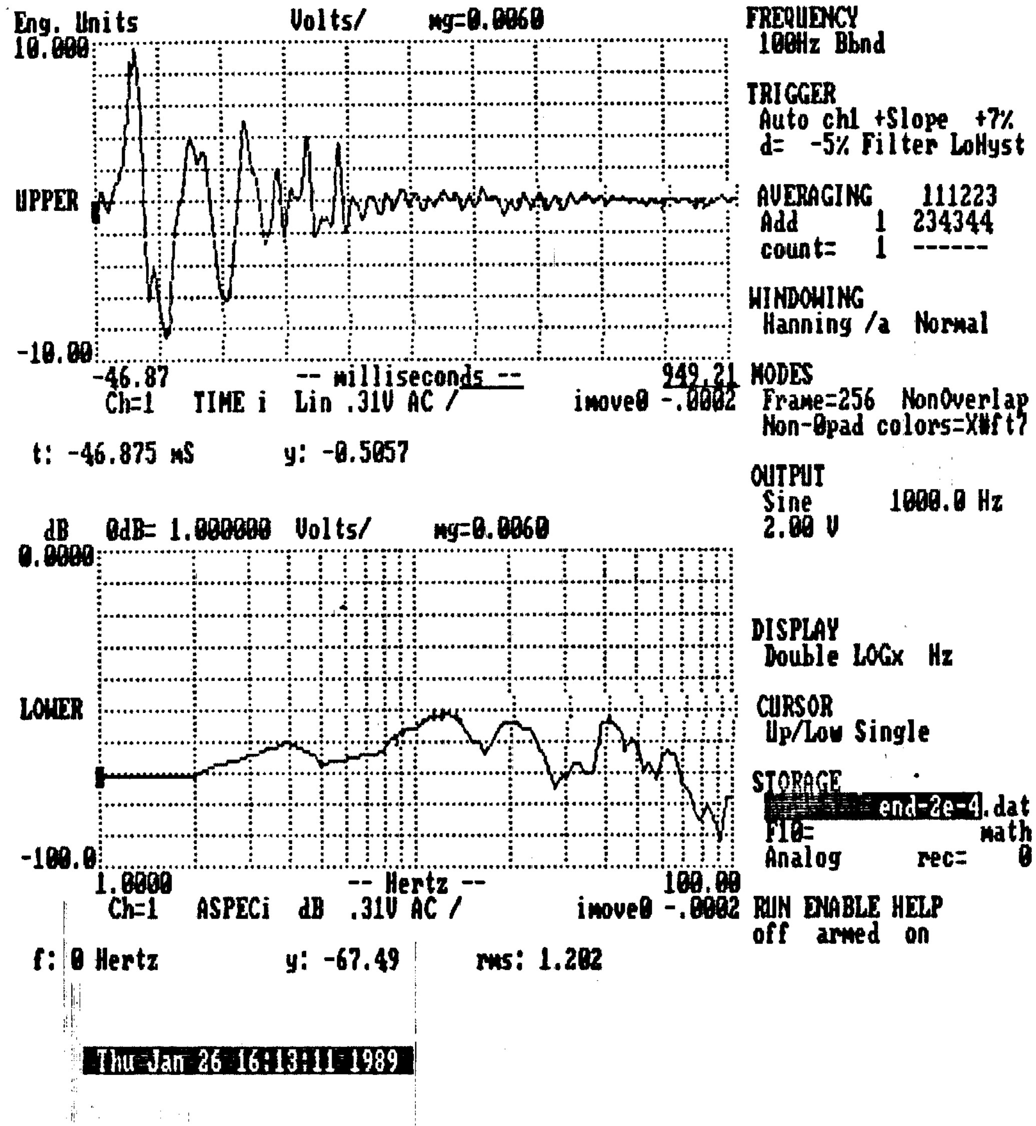

FIGURE 3-4. MINOR STEP (0.0002 rad) ACCELEROMETER MEASUREMENTS

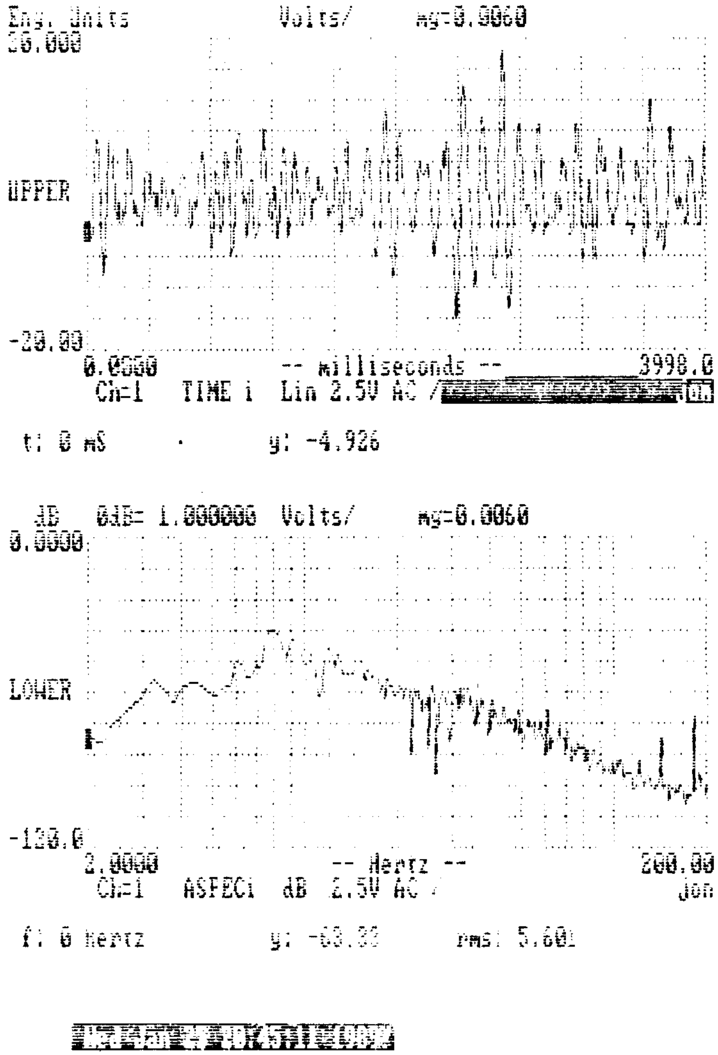

FIGURE 3-5. HUMAN (STABILIZED) ACCELEROMETER MEASUREMENTS

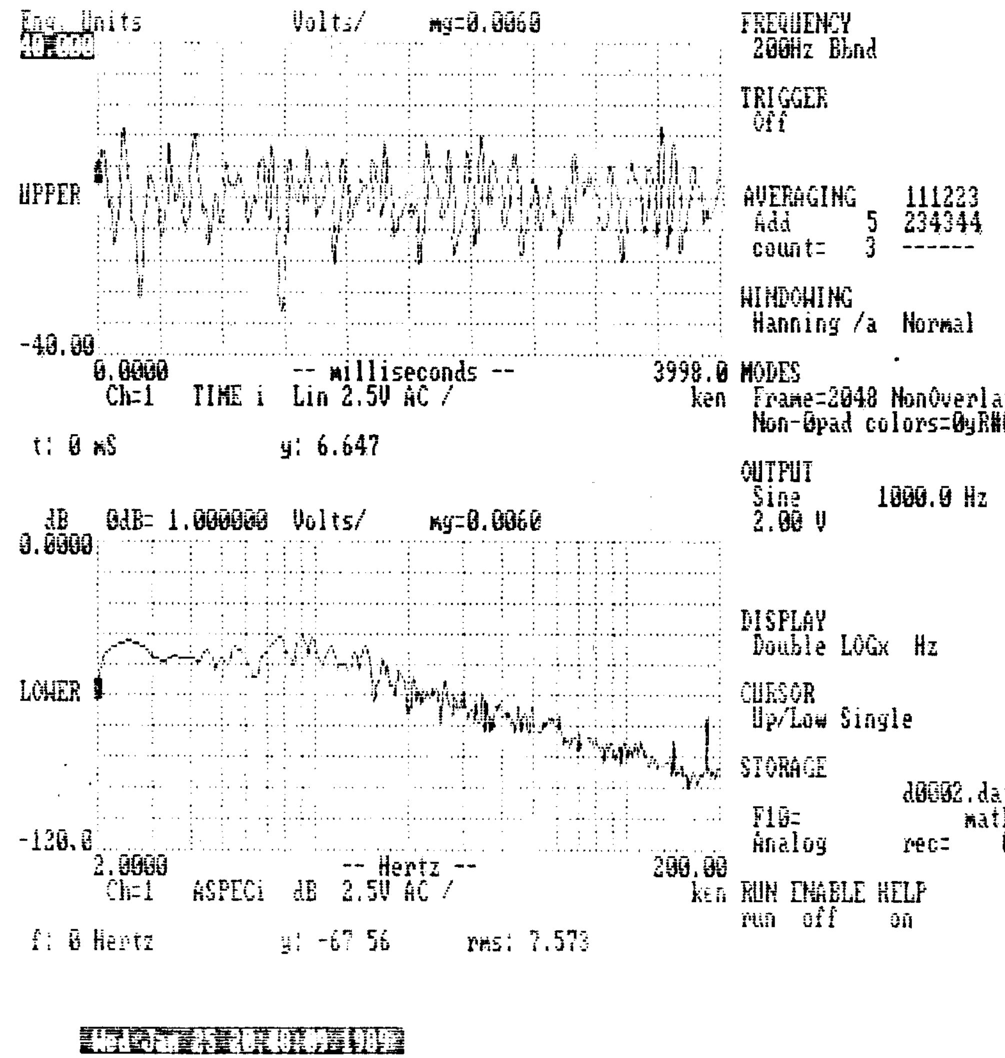

FIGURE 3-6. HUMAN (ARM EXTENDED) ACCELEROMETER MEASUREMENTS

Similar testing with the arm outstretched from the body (parallel to the floor) are presented in Figure 3-6 and resulted in a 35 to 50 milli-g level.

The results of these tests indicate that a robotic system is not only capable of microgravity manipulation, but may actually be preferrable, for certain types of motions, to humans. See Interim Report CR182261 (Section 4 and Appendix 9.6) for further discussion of this data.

3.2.2 Robot Base Reaction Force Analysis

Based on elementary laws of physics, for every action there is an equal and opposite reaction. This means that all proposed manipulations (acceleration and deceleration of mass) have an undesired counteracting acceleration of mass.

In order to quantify disturbances in this category, a NASTRAN model of the Space Station along with a calculated robot forcing function was used during Task II. A complete description of the results are provided in the Interim Report CR182261. For this simulation, the translation of the Large Bridgman Furnace experiment's 1,800-kg mass was taken as a worst-case manipulation scenario for evaluation. NASTRAN models from the Space Station Pressurized Volume Utilization Study and Langley Research Center's (LaRC) OF-2 configuration model were used. The robot arm model was based on a PUMA industrial manipulator. The results are plotted in the previous Figure 2-1 as an envelope superimposed on acceleration requirements.

The results showed a wide range of acceleration responses from 400 to 5,000 micro-g depending on the position and direction of the forcing function. A peak acceleration of 6,000 micro-g was reached during the rigid body response (the first 12 sec). A tenth of a micro-g response was obtained when an elastic rather than fixed base was used. The resonant frequency in the OF-2 model was 0.15 Hz.

A key feature of all these analyses is the finding that regardless of the characteristics of the input stimulus, the space station structure tends to absorb the energy and convert it to the resonant frequency. Thus, all disturbances, of whatever frequency, should be avoided to minimize the absorption and conversion of energy to the low frequency station resonance.

4. SUMMARY OF BENEFITS

The benefits of including a robotic manipulator system in any space-based system (not exclusively the Space Station) will be outlined in this section.

4.1 TECHNICAL AND COMMERCIAL BENEFITS OF ROBOTIC MANIPULATION

The use of robotic manipulation has many advantages when combined with human crew presence. The micromotion manipulation capabilities have been compared previously and a robotic system was discovered to be superior from a pure motion standpoint. Motions and processes that require a great deal of dexterity and/or hand-eye coordination are best performed by a human. This is because of the extreme amount of data and signal processing that would be necessary for an automated system to accomplish these types of tasks.

A robotic system will never be able to replace the human crew. However, there are numerous advantages to having such a system "co-habitate" in an orbiting laboratory such as the United States Laboratory (USL) on Freedom. One such advantage is the capability to operate the system via teleoperations from a ground-based station. This has advantages of its own, such as a 24-h per day operation through the use of ground support personnel in rotating shifts, control of the robotic system from remote sites (such as a Principal Investigator's facility), and the ability to "practice" a control sequence on a simulation before uploading the command sequence to orbit. One other readily recognizable advantage is the high accuracy of repeatability, both in precise manipulation (grip strength, force feedback), etc.) and in movement. That is, a robotic system can move from any location to another (within its range of movement) with very little (typically 0.001 in. or less) error.

4.2 SUMMARY OF COSTS AND COST SAVINGS OF APPLIED ROBOTICS

The cost of the robotic systems identified and conceptualized throughout the course of this study range from a total integrated cost of \$2M to \$20M. These range in capability and features from a single arm manipulator with limited mobility base and simple two finger end-effector, to a very complex dual manipulator system with mobile base and dexterous end-effectors. A dexterous end-effector has several digits and often closely emulates the motions of a human hand. A system such as this would simplify the design of the interfaces with the hardware, as equipment designed for use by the human crew would be useable by the robotic system, with little or no special fixturing required. See Appendix C for a discussion of the various types of manipulator systems and cost estimates.

Since there have been no robotic systems in past manned spaceflight systems, the need for such systems is questioned by many. The payback potential of such systems demands that they be implemented. TBE developed a simulation of the operations of the USL called the PAYPLAN program. Numerous simulations were run with varying inputs, such as the amount of power available, consumables, number of crewmembers, number (if any) of robotic systems, etc. The results of all these simulations runs indicates that the use of robotic system on board the USL will enhance the operations through increased output. That is, the USL system will realize more total experiment operations (measured as cycles of experiment runs) through incorporating a robotic system in the design. This is achieved through the robotic system being able to perform many of the tasks of the human crew (often slower, sometimes faster) and the fact that a robotic system is capable of 24-h per day operation.

TBE performed experiment timeline studies to examine the benefits of using a robotic system to perform certain steps of experiment operations. The results of these studies indicate considerable crew time can be saved by each type of robot end-effector used. These included two and three finger, dexterous, as well as dual end-effectors. The manipulative time savings ranged from 16 percent to over 96 percent of the total man-tended process time required.

The complexity of experiment step (process operation) required drove the complexity (i.e., dexterity) of the robot system required to perform the step. The least capable system (single arm two finger manipulator) is able to accomplish about 40 percent of the needed operations, whereas a dual arm dexterous robot system was found to handle over 90 percent of the crew servicing requirements. This indicates that advanced off-the-shelf robotic manipulator systems are viable solutions to supplementing the crew, and are a solution in removing crew requirements from mundane task accomplishment.

Another study in which TBE participated (Space Station Housekeeping and Mission Support Study, MDC W5178) indicates that a majority of the crew's time on orbit is occupied by "housekeeping" functions. These are activities that are necessary to keep the laboratory running efficiently. The tasks in this area include filter changeout, animal food and waste maintenance, monitoring gauges, meal preparation, experiment sample changeout, and cleanup operations. This is not an exhaustive list, but represents many of the functions for which a robotic system is ideally suited, i.e., tasks that are scheduled often with little or no skill required that are performed the same way each time. These tasks are both repetitive and mundane and, as such, are poor use of the human crew's time. The human crew (scientists and researchers) should be dedicated to examining the results of experiments and characterization rather than cleaning the module walls and feeding the animals.

The cost of the crew on board Space Station Freedom is not yet known, but it is reasonable to expect it to be somewhat less than crew cost on board the Space Shuttle. Although it will be somewhat less it will be quite expensive (initial estimates place the cost at $7,350 to $7,500 per hour). Obviously, the more time the crew can spend performing productive scientific activities and less time housekeeping, there will be more scientific and/or commercial value returned from the USL. PAYPLAN runs have indicated that even a $20 M robotic system would pay for itself in as little as 6 mo, and the increased productivity of the USL would be realized for the life of the station.

4.3 RATIONALE AND IMPORTANCE OF FLIGHT DEMONSTRATION

The acceptance of a robotic system by the scientific and space technical community will be difficult to obtain. In order for a system to be shown safe and functionally useful, it will be necessary to first prove the concepts through flight demonstrations. In 1987 TBE proposed a Teleoperated Laboratory Experiment Manipulator (TLEM) System in response to NASA's Outreach Program. This system is a maniputor mounted on the face of a Spacelab rack that performs many functions on its rack face such as switch manipulation, pick-and-place operations, etc. This system could also operate experiments in adjacent racks, provided the controls were within the envelope of motion of the manipulator. This system would allow the verification of several concepts, safety systems, manipulation capability and accuracy in microgravity, and tele-operations from a ground control station.

However, a forerunner to the TLEM might best be a Get-Away Special (GAS) can experiment. This system would be smaller and able to perform fewer functions, but the operational questions and some of the safety considerations could be answered in this way. The TLEM would be a logical next step, followed by a mobile (rail mounted) system. This stepwise development represents a conservative approach that would allow the concept to be proven before implementation on the USL.

5. PRELIMINARY DEFINITION OF INTERFACE REQUIREMENTS

In order to determine the relative effectiveness of the various robotic systems analyzed, a trade study was performed. The categories of performance, resource requirement, and cost/other factors were established. Within these categories, 30 factors were rated to establish the category rating. To maximize both the objectivity and accuracy of the trade study, a survey was made of agencies with USL responsibilities and experience in flight systems design, including MSFC, LeRC, LaRC, TBE, JSC, and JPL. A relative weighting of performance versus resources versus cost (and other) factors was determined based on this survey. The results indicated a prioritization of the key factors of performance as follows:

Performance	44 percent
Resources	31 percent
Cost Factors	25 percent

These numbers and individual factor weightings were then used to compare the various robot configurations. Using these rating factors, it was found that the most desirable configuration is the dual arm dexterous robot system (rail mounted) in comparison to lesser dexterous systems.

5.1 ROBOT SYSTEM CONFIGURATION AND INTERFACING REQUIREMENTS

Non-experiment-specific system capabilities including operation of multipurpose laboratory equipment were prime drivers in defining the robot system configuration. The specific experiment user needs further defined operational requirements and subsequently helped to define the configuration needed. During the evaluation and system configuration, emphasis was placed on minimizing disturbance to the process being manipulated as well as other adjoining processes.

Starting from state-of-the-art, off-the-shelf, and leading edge developmental robot technology, the configurations were derived. The configurations diverged from normal industrial robots in that the limit in mass, reduction in acceleration, and lack of need in speed of manipulator transit by a space-based robot is quite different from that for a ground-based unit. Whereas a ground based robot must perform a repetitive task at high speeds, commonly with no regard to reactive acceleration to product or environment, the space-based robot must perform a wider range of tasks, but with a lower task repetitive rate while working below the gravitational disturbance threshold allowed by the laboratory and its individual experiments. The space-based robot system must be a low weight and volume configuration to reduce payload weight as well as minimize working profile while working on station or when stored.

Regardless of the final resolution of the requirements of micro-g vs. milli-g requirements for the robot, the basic task control and teleoperation protocol capabilities exist now. Actual flight versions of these technologies will remain very similar. In the area of mechanical and structural design, the basic configurations should remain the same. The major development work required concerns the low-gravity considerations, which is primarily impacted by the motor drives, power transmission and respective controlling hardware and software.

Interfacing requirements include the physical attachment of the robot to the station (via a ceiling or floor-mounted rail or rails) as well as the power, data, communications, and video system needed to monitor and control the robot. Thermal interface is required to remove heat from motors and control system components. The robot itself must interface to the user experiments, processes, and multipurpose lab support equipment. The primary interface goal is to design the robot to fit the equipment such that no human interface is modified. The robot should be programmable and dexterous enough to interface to the equipment designed for human crew use.

Though one can conceive of many types of positioning methods, the requirements of USL operation with crew present requires thorough attention to crew safety. The hardware configuration selected should allow total robot control under any circumstance, constrainable in terms of spatial location and work envelope, timing of robot movement, speed, and reaction time.

Preliminary requirements for a robot system have been established as a working baseline from which the requirements may be finalized. These preliminary requirements are described below.

1. Physical Size: ≤ 20 ft^3
2. Geometry: Low Profile, Minimal Crew Interference

3. Power: < 1 kW Average; < 2.5 kW Peak
4. Thermal: < = Power
5. Data: < 100 kbs
6. Control: Include Ground-Based Predictive Display and Control and remote user access
7. Dexterity, Accuracy, Repeatability:
   a. Twin anthropomorphic manipulator arms with dexterous end-effectors each with minimal three finger multidigit (torque/touch sensitive) operation.
   b. Back-drivability of major extensions with ability to reach any control surface requiring service.
   c. Accuracy +/- .005 in. in worst case assisted by compliance technology
   d. Repeatability: +/- .001 in. in worst case
   e. Automatic target acquisition and recalibration in transit.
8. Low Gravity: Control reactive forces under specified threshold:
   a. Level I: < 1 milli-g
   b. Level II: < 1 micro-g
9. Maintainability: Accessibility and repairability of all motive and control elements and structural elements with minimal access time. Modular, interchangeable joints and control elements where possible. Self-diagnostics and self-preventative maintenance features.
10. Plugs/Interfaces: Modular, quick change, multiple-resource concurrent make and break features (i.e., air, electrical, communications interfaces to be concurrent).
11. Safety: Multilevel failure detection and shutdown in fail-safe mode. Safety sensors to be robust and multispectral to detect unsafe conditions regardless of environmental state. Independent Safety computer to monitor sensors, hardware, and software in relation to task being performed (establishes and monitors safety quotient and predicts probability of unsafe conditions before event).
12. Voice activation and monitoring: Controls interface with voice recognition and control system. Includes verbal outputs concerning process status, intended operation prior to manipulator translation and inquiry (i.e., permission to cross/invade work space).

5.1.1 Rail-Mounted Configuration Details

A review of robot base mobility systems is important in planning the application of robotic systems in the MMPF. Translation along the axis of the USL in a totally controlled and safe mode is required to position the robot manipulator or manipulators to service individual work stations. A track-mounted robot can secure itself to a fixed position within milliseconds when required to do so by the safety computer system. This will provide a method to 'secure' the robot such that positioning or stowing (i.e., homing) is not required.

A rail or rails can be provided when the robot is installed on station. The hooks and scars for this installation can be provided in the original USL (Space Station Freedom) design by adding attach points (i.e., threaded inserts or flange brackets) at appropriate locations along the 'upper' and/or 'lower' ends of the ceiling storage racks. The attachment mechanisms on the rails can then simply plug, screw, or snap onto the attach points on the racks when installed. The rails should be designed as segmented units, so that the normal opening and closing of the racks is not interferred with. The rail or rails provide a support and conveyance track on which the robot base can translate and secure itself.

Power and communications can be transferred along the rails if desired using spring-loaded contact sets similar to those used to convey power and control signals in interchangeable robot grippers. Power and control signals can also be provided using cables as an alternative. Cable reels or self-coiling cables can be appropriately designed and tested to handle the power delivery requirements.

In support of a trade study on the safety issue, the PAYPLAN data base can be used to carefully evaluate each step of the process of a set of representative experiments, much the same as has been done in the micro-gravity studies. Analysis of each step of a process will allow review of safety aspects with respect to the needs by the experiment processes, the USL (facility and services), and the crew. Scenarios can be developed to test the adequacy of each set of safety features incorporated into the robot. A matrix of safety requirements matching the corresponding capability of the robot to meet each safety issue can be built from this data base. A comparative analysis of human ability to meet these safety issues (in terms of dexterity, time, and other relevant operating parameters) would be of interest.

As each element of the robot design is reviewed, additional issues surface. Not only do additional concerns, or ramifications of concerns arise, but further benefits and extension of the initially identified benefits become apparent.

Related to the safety issue, but from the reduced risk side of the robotics equation, for example, the very real potential of the robot to assist the crew during emergencies has not been evaluated. The ability of the robot to be driven telerobotically and remain functional in the most hostile of environments to provide a backup system for crew safety would be of great value.

5.2 PRELIMINARY REQUIREMENTS FOR FLIGHT DEMONSTRATION

To provide a design for a space station system with as many unknowns as the laboratory robot manipulator system, demands that the verification and proof of principle be clearly demonstrated. For this purpose, the Orbiter has been designated as the proving ground for advanced technologies requiring flight demonstration testing before transfer to space station. The technologies requiring flight demonstration are low-gravity performance of the near reactionless robotic system and safe operation in the presence of crew, both while under teleoperated control.

Critical issues to be addressed for a flight demonstration include:

1. Minimization of weight (mass) and volume
2. Low-gravity manipulator performance measurement using end-effector and base accelerometer and reaction force monitoring during manipulation and sample movement
3. Resource conservation for power, thermal and volume
4. Maximization of ability to share equipment and resources
5. Ease of interface and operation/maintenance by crew
6. Safety of the system.

Under Task IV, two basic configurations were discussed: the Spacelab rack-mounted flight demonstration robotic system and the external, Orbiter Get-Away Special can mounted robotic arm.

The Spacelab rack-mounted system or Telerobotic Laboratory Experiment Manipulator (TLEM) as shown in Figure 5-1, requires considerable flight qualification work since it is in the crew habitable volume. The GAS can mounted system may be completely sealed and would be subject to less stringent flight qualification testing. This is economical not only from a cost standpoint, but also with respect to schedule impacts.

The GAS can experiment would permit the verification of low-g robotic manipulator performance and the measurement of the associated accelerations caused by manipulation of known masses at selected rates of motion. These acceleration measurements would be taken both at the end-effector to determine sample accelerations and at the robot base mounting to determine reaction forces. The GAS can concepts are very straightforward because of the constraints of power, thermal, and control/data that are available via standard GAS can interfaces. In general, these constraints limit the experimenter to simple turn-on and turn-off and all other services must be built-in to the experiment. Thus, thermal regulation is passive, control must be by the experimenters prearranged plan, and the data taken must be recorded for later analysis. Within these constraints, however, there are a number of concepts that can be evaluated. Acceleration data can be intermittently taken throughout the mission to define the background. The arm manipulations can be defined in terms of accuracy, repeatability, and acceleration levels at the end-effector and the base. Limited teleoperated control could still be implemented as well through a dedicated data cable (or remote communications link) to the GAS can. While this increases the cost of a GAS can flight, it also adds flexibility to allow changes to the operational scenario as the flight progresses.

A negative factor to the GAS can scenario is that a failure in the system will generally go undetected and the experiment success or failure won't be known until the data tapes are evaluated after the mission. The added advantages of the Spacelab manipulator system experiment are that it provides more flexibility in functions and can be used to actually operate other flight experiment systems. Another advantage is that operations in a manned laboratory are very similar to those planned for the Space Station Freedom. This provide another measure of reality by verifying safe operation of flight experiments in a manned laboratory in real time.

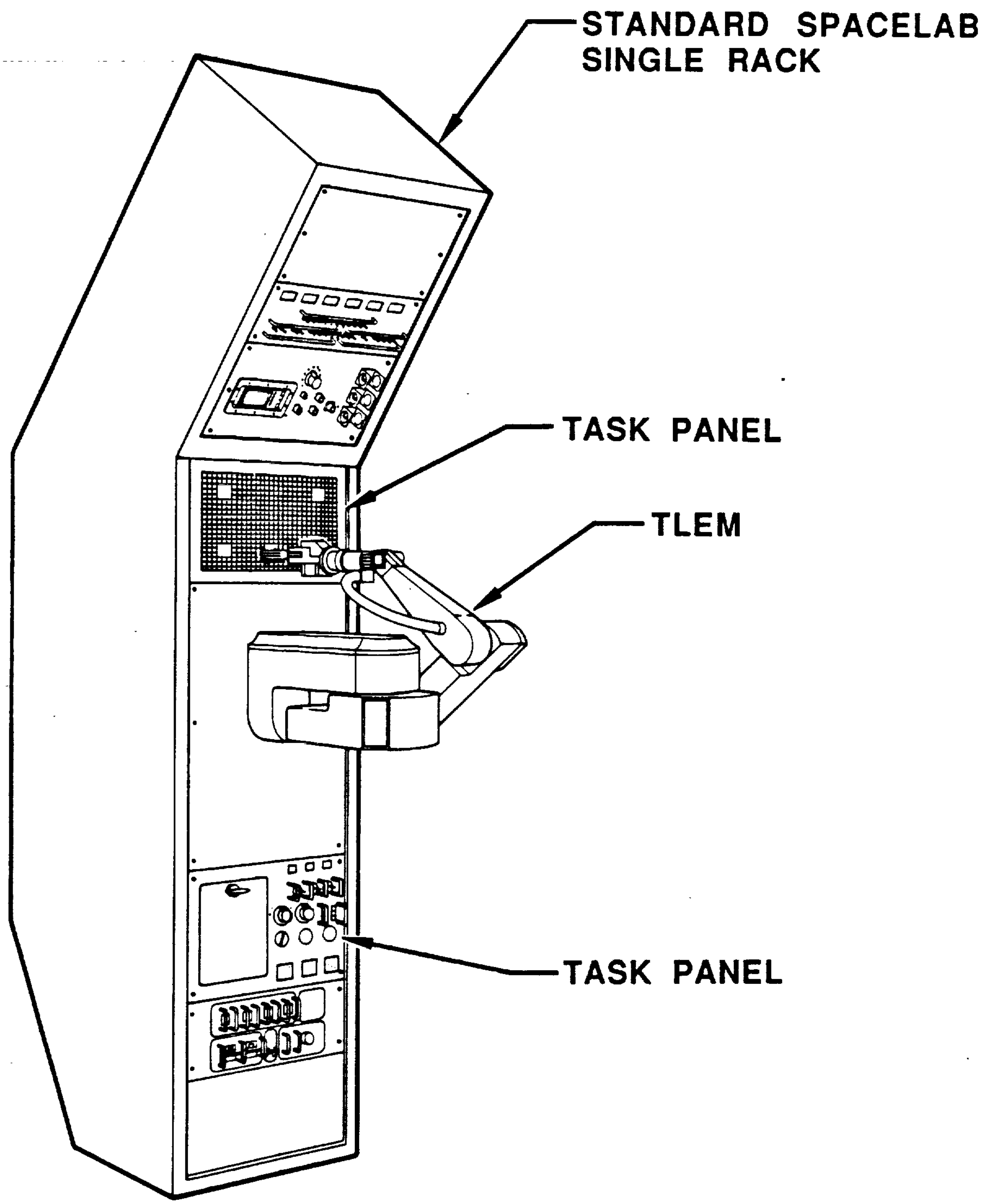

FIGURE 5-1. MANIPULATOR FLIGHT CONFIGURATION FOR ON-ORBIT OPERATIONS

The primary drivers for selection of the GAS can mounted demonstration are reduced cost and schedule, whereas the primary driver for selection of the rack-mounted robot system is the benefit of testing a broader spectrum of robot system attributes. The GAS can mounted demonstration is estimated (ROM) at about $250K, while the TLEM demonstrator is approximately $1.5M (ROM).

The TLEM concept was developed to demonstrate robotics on Spacelab. The concept is described in the Interim Report (NASA CR182261). The TLEM concept can be reduced in scope and budgetary requirements to exclude a portion of the teleoperation capability. This lower cost experiment will still allow measurement of the impact of robotic operations on the micro-g environment. The following section provides a definition of requirements for this TLEM.

5.2.1 Representative Orbital Flight Experiment

The flight experiment should provide a representative set of tasks common to microgravity experiments. This will allow testing a specific set of robotic attributes, such as dexterity, repeatability, accuracy, speed, and maintenance of the microgravity environment as well as comparison of manipulation capabilities to the crew.

The experiment selected should also be a low cost unit packaged with the robot manipulator into a single rack. Typical specifications include:

1. Low volume, size, weight, and complexity
2. The experiment should be well defined and representative of actual future experiments to be performed.
3. The experiment selected should require a specific range of manipulative skills and operational requirements that are best handled by a robot manipulator. (For example, an experiment that requires a large number of low acceleration motions and very precise positioning of samples would be a good candidate.)
4. The experiment tasks should be interruptible and resumable at will with minimal impact on the experiment.

5.2.2 Microgravity Manipulator and Subsystems

The manipulator unit should be designed to service the selected experiment through as many of the task elements as is practical (from a cost standpoint).

The manipulator command and data management system should include hooks and scars to allow addition of teleoperation via both space-resident as well as ground-stationed control units on subsequent test flights.

The manipulator should be designed to incorporate the use of microgravity capable subcomponents and principles. For example, low mass structure and drive systems should be used. High strength carbon fiber materials may be substituted for metal in structural components. Lightweight thermally conductive plastics may be used in power transmission components. Motive drive actuators with low acceleration potential will be required. Kinematic study should determine the best possible dimensional characteristics of the robot system to reduce acceleration disturbances. Use of dynamic counter-reactive arm segments should be reviewed for potential application in the design of the robot.

The robot control system should include subroutines that support each task element in a practical manner. For example, since a microgravity environment is not necessary in all experiments for all steps in the process, the task acceleration and transit time elements should be programmable for in-flight testing of corresponding actual (measured) acceleration. Each task element should be user selectable independent of the experiment's process program.

The robot data system should be designed to address the following major capabilities:

1. The robot position, speed, torque (on all axes) should be constantly monitored and reported. Tactile sensor output (from sensors located on the end-effector) should also be monitored.
2. The accelerometer readings corresponding to each robotic move should be constantly monitored and coupled to the corresponding robot motion information for analysis. A comparison of the experiment acceleration to shuttle acceleration should be made to allow accounting for external disturbances (i.e., disturbances generated by all sources other than the robot manipulator.)

3. The corresponding experiment status should be added to the accelerometer and robot status data.
4. The data system should store and/or transfer this information to the ground station. The overall experiment schedule and status should be available to the flight crew and manual override allowed for shutting down or rescheduling the experiment runs.

The acceleration system should measure the micro-g disturbance levels in three axes at the end-effector location. The data rate of sampling should be programmable.

The safety system must meet both general NASA NHB 1700.7A and specific industrial BSR/RIA R15.06 safety requirements. Additionally, the robot must be designed to limit torque. The controller should include a safety computer. The robot should be back-drivable and include a 'limp' mode. Should a torque limit be exceeded, the safety computer will place the robot manipulator into limp mode until reset.

5.2.3 Robot Development

A potential stepwise approach towards development of a micro-gravity robot for application in the USL on Space Station Freedom is given below in the form of milestones:

1. Ground Demonstration of primary technical requirements.
   a. Demonstrate Robotic Capability to manipulate an experiment operation or operations at sub-milli-g disturbance level.
   b. Demonstrate Predictive Display and Control with video overlay
   c. Prepare requirements for a GAS can experiment.
2. KSC-135 Experiment
   a. Demonstrate Robotic Capability to manipulate in a low-g environment.
3. GAS Can Experiment
   a. Demonstrate in-flight capability of a robot by successfully manipulating samples within a sub-milli-g experiment.
   b. Demonstrate in-flight capability of predictive display and control on a limited basis (i.e., show proof of concept).
   c. Demonstrate ability of robot to be manipulated by crew in local telerobotic mode.

3b. Hitchhiker Experiment

a. Demonstrate in-flight capability of a robot by successfully manipulating samples within a volume equivalent to one or several racks.

b. Demonstrate in-flight capability of predictive display and control via operation of a flight experiment.

c. Demonstrate robot operation by crew via local telerobotic operation.

4. Spacelab Experiment

a. Demonstrate the ability of a robot to service a full scale rack-mounted experiment.

b. Demonstrate the full Predictive Display and Control system

c. Demonstrate the Safety system capability by an in-depth test of fail-safe subsystems.

d. Demonstrate local crew operated (local telerobotic) mode and confirm serviceability of robot.

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6. DISCUSSION OF RESULTS

Based on the MMPF data base-defined requirements for manipulation to support experiments and processes, a robotic manipulation system can be conceived which will handle repetitive and time consuming operations. Interprocess/experiment interference and disturbance levels can be minimized using this automation approach.

6.1 MANIPULATION DISTURBANCE LEVEL LIMITATIONS

A properly designed manipulator system is capable of doing the defined tasks with minimal perturbation of the low-gravity environment. The result of this study and evaluation of data obtained is that there is, however, a serious problem in the experiment community concerning the perception of how "good" the low-gravity environment is likely to be on board the space station. Reviewing the potential sources for disturbances we found several that are of a much higher level than the potential robotic system, and propulsion and thermal deflections were not even considered.

The MMPF data base reflects a very high user expectation, stating a need of $10E^{-6}$ g (or micro-g) levels for many processes. Measurements on board the Orbiter have reflected that it has provided a $10E^{-3}$ (or milli-g) environment at best. The difference in the level asked and that provided in practice to date is roughly a level of three orders of magnitude. Bringing the station environment into the microgravity range can present some very real obstacles and difficulties.

In the acceleration tests accomplished in the laboratory, it was found that human fingers pulsate and vibrate in the 10 to 50 milli-g amplitudes, even when at rest above a fixed support (i.e., hand on table holding the accelerometer). The reader can appreciate this level of disturbance by simply placing both hands on the table with fingers of both hands touching and index fingers braced with the thumbs such that the index fingers just barely touch. The bouncing of the two fingers at the point of touch is in the range of 20 milli-g for most individuals. A microgravity disturbance is four orders of magnitude less (10,000 times less) than the best human control measured in the lab (10 milli-g).

Robotic control of off-the-shelf microstepping motors allowed for disturbances as low as 2 milli-g, which is an order of magnitude less than that of the human subjects.

Where a $10E^{-5}$ to $10E^{-7}$ g environment is specified, free-flyer designs may be required. Whether damping techniques can provide this level of environment on the space station is questionable, but worthy of further study. Additionally, for robotic servicing within the microgravity environment, further work is required to develop hardware and control systems to operate below this disturbance range. It may be that a combination of station structural damping technology, experiment housing damping techniques, and appropriate active and passive damping techniques may be applied not only to the robot manipulator but also to experiment containers and tools.

6.2 ISSUES

During the course of this study, significant issues of both technical and nontechnical nature which are sources of concern have been identified. Some of these represent newly identified concerns as study progress has been made. Other concerns are related to state-of-the-art needs, and are related to incremental findings or identification of problems.

6.2.1 Problems Identified

A summary of problems and issues identified during this study are reviewed here. The magnitude of importance (i.e., impact on program), current disposition, and discussion of potential methods of resolution are given as well.

1. Current state-of-the-art robots using microstepping motors and harmonic drives exceed microgravity levels for both base reaction and end-effector sample manipulation. Proposed solution elements are as follows:
    a. Evaluate latest state-of-the-art motors and low-g drives and transmissions, including harmonic drives and roller drive transmissions.
    b. Evaluate latest state-of-the-art in materials as well as manipulator design configurations.
    c. Study, experiment with, and evaluate passive and active damping techniques for experiment isolation, robot isolation, and lab isolation.

d. Investigate new motive actuator technologies including shape memory, magnetic isolation and drive, and piezoelectric motors.

2. The Orbiter via the Mobile Servicing Center (MSC) end-effector and other external disturbances are a severe source of disturbance into the station in relation to a microgravity environment. Methods to relieve disturbances within the joining mechanisms should be reviewed.

3. Early tests of the Intelledex 660 revealed that the stock encoders defeated the microstepping capability of the stepper motors. Bypassing the encoders allowed use of this feature.

4. Microgravity disturbance levels to be expected on orbit are not fully understood, and levels of disturbance to be expected by general crew servicing is not fully appreciated. Measurement of actual acceleration levels during the course of experiment servicing is needed. Comparison of these disturbance levels to that of a telerobotic laboratory manipulator is also recommended to confirm comparative automated methods of servicing.

5. User needs for low gravity should be validated. The frequency and duration of actual low-gravity needs should be validated for a range of experiments to determine how rigid the microgravity requirements are. Perhaps a milligravity level is sufficient in more cases than is currently assumed.

6.2.2 Technology Needs

As identified in section 3, one of the greatest issues or need areas for microgravity robotics (considering the candidate experiments and/or processes, shared lab resources, and MMPF housekeeping) is in handling delicate crystalline structures during and/or after processing. One of the best examples is the Protein Crystal Growth process, in which very low order disturbances can destroy the structure of the protein crystals grown.

The technology to support this manipulation and requiring immediate attention, if microgravity robotics are to become a reality for use on a space station or possibly a future free-flyer, is primarily that of motive drive, transmission, and control. Though successful demonstration of state-of-the-art equipment has shown that a $10E^{-4}$ level is within reach by microstepping motors, further development is required. To achieve the micro-g level, a thorough study of reactionless (counteracting) techniques and alternative methods of drive, transmission, and control must be made. Operation in a low-gravity environment will be of great value in determining the magnitude of reduction in g-levels needed for robotic operations in micro-g experiments.

Since data gathered during this study indicates that humans are limited to a 10 milli-g disturbance level of manipulation, prevention of disturbance levels to that below the 1 milli-g level is achievable only by alternative, nonhuman methods. Alternative methods include appropriately designed automated experiments in addition to robotic assist devices appropriately designed. Both the need (user experiment material handling) and limitations of options (i.e., limited crewtime) indicate some level of robotic support is needed on the space station. The potential impact on the overall space station development schedule can be minimized by implementing an orbital test of a TLEM-type flight demonstration experiment. Secondly, a phased implementation of robotics onto the station should allow building on consecutive successes, starting with well-developed technology and upgrading progressively.

Finally, a logical sequence which could lead to reactionless microgravity robotic systems is an implementation of a plan that includes evolutionary enhancement of robotic capability on station. The station and station systems design work is now underway. Robotics technology that is not ready for development today will be unlikely to be qualified for spaceflight by the mid 1990s. It is therefore best to think of the first flight systems as the simpler and more readily achievable ones. All up, new designs take several years to get through the verification and qualification cycle. The only designs that can be turned around and flown in less than about 3 years, are those that are modifications to previously flown designs.

Through proper, detailed planning and the use of hooks and scars incorporated into the initial robot system, it will be possible to develop an immediately useful robotic system that is both economical and has reduced risk in development. One preliminary sequence under investigation is as follows (Note that this schedule is a relative timeline and that potential slippage should be allowed pending overall program schedule requirements):

1. Plan and implement a TLEM (Telerobotic Laboratory Experiment Manipulator) on a scheduled Shuttle-Spacelab flight circa 1992. This will provide the opportunity of testing actual dynamics of a robot manipulator within a laboratory environment.
2. Space station, circa 1996: Rail-mounted, single-arm three-finger robot. This system is to be modular such that the hooks and scars

for a dual-arm dexterous system can be interchanged with this robot at a later date. Based on improvements in existing technology, this configuration can be ready for startup with the per42manently manned Space Station.

3. Growth Space Station, circa 1998: (Upgrade #1) The single-arm manipulator and three-finger end-effector can be replaced by the dual-arm dexterous system within 18 to 24 months of final certification of the single-arm system. This will allow time to implement changes and/or new technology into the dual-arm dexterous system. Problems identified on station can be addressed, corrected, and implemented for this next generation robot system. User needs on long-duration low-disturbance process runs can impact the design.
4. Final Configuration, circa 2000: (Upgrade #2) Based on results of the dual-arm dexterous robot system installation and application, design of a wall-walker robot can be completed and an experimental semi-autonomous configuration installed on station to supplement the rail-mounted system. The wall-walker can be used to verify system capability and will function as a test bed for development of long-duration mission applications. The wall-walker unit would not replace the dual-arm dexterous robot, but would instead be used to supplement the dual-arm unit in operations. It is expected that because of its mobility, the wall-walker will be easier to maintain (ease of access), replace, and upgrade. It should also be noted that because of its mobility, the wall-walker robot (or its successors) should be available for testing on work sites other than the USL.

This proposed sequence of development would permit a pay-as-you-go type of development. It would also serve as the catalyst and focusing point within NASA to support the development of the required technology advancements in motors, drives, counter-balancing mechanisms, et cetera, required by the low-gravity processing community. With acceleration background levels that may far exceed user-defined limits for experiments, robotic development could be in vain, if the disturbance sources on the station are not positively controlled.

6.3 IMPACT ON USERS AND STATION DESIGN

Under Task V, the development of a laboratory robot for operation in the Space Station Freedom would mark a significant turning point in man's exploration and utilization of space. Past programs were either manned or unmanned "robotic" missions. Mercury, Apollo, and Shuttle are all manned programs. Surveyor, Mariner, Viking, and Voyager are all unmanned robotic missions. For the first time, the proponents of these two kinds of programs are beginning to accept the necessity of cooperative missions to achieve maximum science return. Deep space exploration will remain a robotic domain, but the exploration of near-Earth, Lunar and Martian environments requires both man and robot. The reasons are predominantly the desire to get efficient return on investment. Man provides the intellect and observational skills, while the robot provides the tireless slave labor for the maximization of mission return.

The immediate impacts are to the basic design of the space station to accommodate the interfaces required to support a robot: structural, power, data, video, and communications. Also the user community must be aware that robotic servicing and operations are possible. A significant impact will be in the area of mission planning in that the robot operations will form a part of the "crewtime resource" and it will provide either an unskilled crewmember level or perhaps in the ground control mode under the command of an expert scientist, a very high skill level.

As with any resource as it becomes available and proves useful, it becomes less available as its usefulness is recognized by other potential consumers. Fortunately, in the case of robots, as they are more in demand, more can be added without significant addition of other resources as is the case of crew that must eat, breathe, and produce wastes. The power and data/video/communications used by a robot are all related directly to productive work.

7. CONCLUSIONS AND RECOMMENDATIONS

From analyses of the user experiment flows and the results of analyses and our test laboratory accelerometer measurements, it is clear that present user-defined low-gravity requirements ($10E^{-6}$ g or better) exceed the present capabilities that either man or machine can accomplish. New technology in motors and drives might provide improvement to what appears at best to be a milli-g environment for most of man's machines in low-Earth orbit.

The quandary over predicted experiment acceleration requirements in the absence of any previous experience with "microgravity" versus the most probable best case low-gravity environment cannot be resolved until a free-flyer demonstration flight is operational, such as ESA's Eureka. This will provide new low-g measurements and samples to evaluate. At that time, the question about the true merits of micro-g versus milli-g should be answered.

Whatever the lowest gravity orbiting environment that is practically attainable is, it certainly will not be a permanently manned facility, but rather a free-flyer, man-tended for servicing. It may have robotics which is active only during specified periods during the mission timeline.

If the Space Station Freedom is built along current guidelines for design and modes of operation, it is clear that low-g experiments will be included in the manifests. To provide the maximum low-g accommodation possible, it will be necessary to provide robotics. As demonstrated in our laboratory measurements, current robotics systems can sustain milli-g level manipulation of samples, whereas humans cannot. Human sample manipulation will be subject to at least 20 to 60 milli-g accelerations, which are essentially undetectable to the human.

It is our finding that the technology for manipulation has not specifically addressed the low-gravity problem. Development work on the motor and gear mechanisms to achieve very low disturbances is needed if robots are to operate a "microgravity" facility.

Our study has identified several other key issues which can only be verified with a flight demonstration experiment. These key issues are related to:

- "Real-time" ground control of telerobotics, via NASCOM and Tracking and Data Relay Satellite System (TDRSS), using predictive display
- Safe, crew interactive operations in a low-g environment
- Performance of a telerobot in low-g.

A separate finding related to robotics is that humans are generally unaware of just what a milli-g or micro-g is. Our test subjects were surprised at how "disturbing" these g-levels were to the acceleration environment. Since crewmembers are likely to be involved directly in most planned research in low-g, special "awareness training" for astronauts on these missions should be included. Actual levels of disturbance they generate should be defined, and they should learn the techniques to minimize disturbances in manipulations and movements within the laboratory.

The optimum scenario for space station operations appears to be a combination of crew and robots. As found in the analysis of benefits, there is a serendipitous effect of having a combination of men and machines. While robots can work diligently and deliberately around the clock in low-g fashion, only the crew can instantly address unique problems requiring reasoning, agility, and dexterity. The capabilities of both are limited by their creator's design and must be supplemented for maximum benefit.

8. ACRONYMS

ESA	European Space Agency
FES	Fluids Experiment System
FTIR	Fourier Transform Infrared Spectrometer
FTS	Flight Telerobotic Servicer
GAS	Get-Away Special
GPIB	General Purpose Interface Bus
LaRC	Langley Research Center
LeRC	Lewis Research Center
LVDT	Linear Variable Differential Transformer
MEPF	Multiple Experiment Processing Facility
MMPF	Microgravity and Materials Processing Facility
MRMS	Mobile Remote Manipulator System
MSC	Mobile Servicing Center
NASDA	National Space Development Agency
OMV	Orbital Maneuvering Vehicle
PAYPLAN	Payload Production and Planning
PCG	Protein Crystal Growth
TBE	Teledyne Brown Engineering
TDRSS	Tracking and Data Relay Satellite System
TGS	Triglycene Sulfate
TLEM	Teleoperated Laboratory Experiment Manipulator
UNBIS	User Needs, Benefits, and Integration Study
USL	United States Laboratory

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APPENDIX A

UNBIS FACILITY DESCRIPTIONS

October 1989

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1. INTRODUCTION

The following paragraph describes the science requirements and operations of the selected experiments. Also included is the rationale for selection of this MMPF facility for further study in this contract.

1.1 GENERAL ASSUMPTIONS AND GUIDELINES

The following are common assumptions and guidelines defined for all of the facilities:

- Acceleration of 1 g at a frequency of 60 Hz was assumed during ground handling and transporting to the Station
- Acceleration of 1×10^{-2} g at a frequency of 60 Hz was assumed while on orbit but not operating
- Acceleration and frequencies as determined in the MMPF data base were used for the processes and materials considered
- The robot arm was considered to be at rest in the x=49, y=79.5, and z=0 (front center of the rack; dimensions in cm) position
- The logistics module weight is 20,000 lb
- 100 man-weeks are required to ready a facility for launch
- 33.33 man-weeks are required to ready samples for launch
- 16.67 man-weeks are required to ready other consumables for launch
- 10 man-weeks are required to integrate the facility into the shipping hardware
- 10 man-weeks are required to integrate the shipping hardware into the logistics module
- Assuming 1-h launch time to orbit 14 facilities with an 8-man crew requires 60 x 8 / 14 = 34 crew minutes per facility
- Assuming 3 days to secure the items once on orbit or 3 (days) x 24 (hours/day) x 60 (min/hour) x 1 (crewman)/14 facilities = 308 crew minutes per facility
- The facility's mass, volume, power requirements, and other resources come from the MMPF data base unless otherwise stated.

2. ACOUSTIC LEVITATOR FACILITY

2.1 FACILITY DESCRIPTION

The Acoustic Levitator is a furnace chamber occupying 0.082 m^3. The furnace is electrically heated up to 2500 ^oC. A glass sample is inserted into the chamber and positioned using acoustic forces generated by an acoustical driver with a reflector in the opposite wall of the furnace. This allows the sample to be processed without contacting the furnace walls. Contact with the walls of the furnace causes nucleation points to form in the sample along the areas of contact. These nucleations will affect the quality of the material produced by disrupting the crystalline structure of the materials. Contact with the walls can also introduce unwanted contamination into the sample.

The facility has acoustic drivers/reflectors in each of three orthogonal planes. These drivers/reflectors allow the sample to be injected into the furnace, processed in a given position, rotated (if required) during process run, and moved from the furnace into a cooling chamber for solidification, all without the sample ever coming in contact with the furnace or any other object. The three drivers/reflectors also allow the user to shape the sample into various geometric shapes, thereby studying the sample melts physical and processing parameters. Using a force feedback system from the acoustic drivers/reflectors, the user can accurately measure the acceleration, viscosity, density, and various other properties of, or acting on, the melted sample.

2.2 ACCELERATION REQUIREMENTS

The Acoustic Levitator requires an acceleration level of less than 10^{-4} g during the melt, processing, and resolidification stages of the run. The solidified glass sphere samples are insensitive to the acceleration forces. The characterization that is required on orbit does not require specific acceleration levels.

Although the process is considered to be containerless, the acoustic pressure in the carrier gas (usually GN_2) does transmit forces through the gas and into the sample. This will isolate the sample from the higher frequency accelerations but will not help the steady state acceleration driven forces from propagating into the sample. The frequencies that are considered to be damped from the samples in this process are those greater than the driver frequencies (usually 20,000 Hz). Another consideration for the acceleration environment is that the acoustic force can only overcome small acceleration driven forces. As the external forces exceed the acoustic force, the sample can no longer be controlled and it will leave the acoustic well and strike the wall. The value of the acoustic force is the upper limit on the acceleration for the least sensitive samples.

2.3 SELECTION CRITERION

This facility was selected for study under this contract for the following reasons:

- The facility processes glass samples which exhibit unique properties when influenced by acceleration (glass has an amorphous structure)
- The facility has unique operational requirements, such as operation of optical refractometers.
- The facility is a good candidate for automation because of the large manpower requirements and repetitive tasks.

2.4 ASSUMPTIONS AND GUIDELINES

In addition to the common assumptions and guidelines defined in section 1.1, the following were considered for this facility:

- The sample is fluoride glass
- The entire facility outlined in the MMPF report is used
- Each sample is characterized before the running of the next.

3. ALLOY SOLIDIFICATION FACILITY

3.1 DESCRIPTION

The Alloy Solidification Facility consists of three furnaces; an isothermal furnace, a Multiple Experiment Processing Furnace (MEPF), and a precision solidification system.

The isothermal furnace uniformly heats metallic samples up to 1600 ^{o}C at diameters of up to 2 cm, then rapidly and uniformly cools the samples. The sample is melted, the mixture is allowed to mix through diffusion, and the sample is rapidly quenched thereby "freezing" the immiscible materials. This allows the user to produce homogeneous alloys that would settle out in the presence of gravity-driven buoyancy forces. The rapid quench capability can be used to control the cooling rate and produce various crystal structures.

The MEPF is a furnace that can be reconfigured to process a variety of materials, such as alloys, electronic materials, and organic samples. The furnace runs at up to 1600 ^{o}C with samples up to 2 cm in diameter. The MEPF also has rapid sample cooling capability. The MEPF heats the sample uniformly to the run temperature; however, the sample is directionally solidified. This directional solidification, also known as the Bridgman technique, is used to help purify the melt. As the melt is solidified, a crystal matrix is formed. This matrix "finds" a particle of the right type and charge to complete the matrix. The unsuitable ions are pushed ahead of this forming matrix and, therefore, are removed from the structure. In this way, the sample is purged of the unwanted materials. This purging force pushing the ions out of the matrix is very small, and the acceleration driven forces of buoyancy and convection can easily overcome the pushing force, thereby causing dislocations in the forming matrix when this process takes place in the presence of gravity. The rapid solidification capability is used in the same way as on the isothermal furnace described above.

The precision solidification system is similar to the European Mephisto furnace which flew on the Spacelab D-1 mission. This furnace measures the properties of the solidifying materials for use in materials studies. Properties measured include the forces described above, Marangoni convection (convection driven by thermal forces on the molecular level) and other solidification perturbations. This furnace processes a very small sample and is limited to 1100 °C maximum operational temperature. The system is capable of controlling a high temperature gradient (up to 300 °C) with a near flat solidification front.

Operationally, the isothermal and the MEPF furnaces are automated to provide up to 20 samples each without interruption, and will only require a change of the carousel(s) to begin the next run(s). The precision solidification system will only run one sample at a time but supports multiple samples via carousel sample handling.

3.2 ACCELERATION REQUIREMENTS

The acceleration requirement for all of these furnaces is the same. This is because the materials, matrix size, ion size, solidification rate, and fluid viscosity determine the level of DC acceleration that the melt can withstand. These furnaces are all processing the same type of materials, they all respond to the accelerational input in the same manner, and the maximum DC acceleration level is 1×10^{-5} g.

3.3 SELECTION CRITERION

The Alloy Solidification Facility was selected for the following reasons:

- The facility processes metals and alloys. This group of materials will benefit from space processing
- The facility requires the use of a rapid quench technique that could be a perturbation to the host facility as well as to others
- The materials used in the facility have unique characterization equipment requirements (metallographic microscopes).

3.4 ASSUMPTIONS AND GUIDELINES

In addition to the common assumptions and guidelines defined in section 1.1, the following were considered for this facility:

- Only the MEPF and the isothermal furnaces were considered for this analysis
- This arrangement occupies one double rack

- The mass used does not include the x-ray system, the data collection system, or the precision solidification system
- The facility mass is 270 kg plus 10 percent for packaging (27 kg) plus samples (10 kg assumed x 5 = 50 kg) = 347 kg total mass.

4. ATMOSPHERIC MICROPHYSICS FACILITY

4.1 DESCRIPTION

The Atmospheric Microphysics Facility contains an expansion chamber, a sample injector, a controlled diffusion chamber, and other devices needed to produce clouds and study their formation and coalescence. Several types of experiments can be performed in this facility.

The first class is cloud formation experiments. These experiments take advantage of the reduced gravity of space to slow down the growth of the water droplet by allowing the diffusion of water to the seed droplet to be the dominant process driver.

Another experiment to be run in the Atmospheric Microphysics Facility is the production of a polydispered cloud to study the interaction of the droplets with light, temperature, and other atmospheric conditions.

Other experiments are to study the effects of a nuclear explosion on atmospheric conditions, to determine the contents of the atmospheres of other planets, and to better understand weather conditions for improving weather forecasts.

Within this facility, a particle is introduced into the expansion chamber. The chamber is then filled with moist air from the diffusion chamber and then slowly and adiabatically expanded. This expansion forces the water to condense onto the particles and form droplets. This will allow researchers to determine the time that these dust and smoke particles stay in suspension before the atmosphere "washes" them out of the air. This will then be used to update the theories on the effects of nuclear explosions (nuclear winter, greenhouse effect, etc.).

4.2 ACCELERATION REQUIREMENTS

The Atmospheric Microphysics Facility will require a low g (10^{-4} g) environment for many intervals of up to 60 min at a time. There are many experiments that will be run back to back with only enough time between to allow the equipment to reach the desired operational temperature. The time between the experiments will require the operation of the hardware by the crew. This tends to be very laborious and time consuming. Therefore, automation would result in great time savings. The tasks required are unique: vision with depth of field, high-resolution video, and low accelerations induced into the sample.

4.3 SELECTION CRITERION

The facility was selected for future study in this effort because it will require the sample to be free floated in the chamber. This is a unique requirement, since few facilities actually freely suspend the sample in the container. There are three other MMPF facilities that do this, the Fluids Physics Facility, the Variable Flow Shell Generator, and the Free Float Facility. The Fluid Physics facility will also be selected for this reason.

4.4 ASSUMPTIONS AND GUIDELINES

In addition to the common assumptions and guidelines defined in section 1.1, the following were considered for this facility:

- The experiment run is a cloud formation experiment with varying temperatures and pressures to simulate varying altitudes
- The seed material is small water droplets
- Cloud analysis is done as part of the run with the cloud still in suspension, implying that no additional characterization is required.

5. CONTINUOUS FLOW ELECTROPHORESIS FACILITY

5.1 DESCRIPTION

The Continuous Flow Electrophoresis Facility uses an electrical charge across a flowing fluid field to separate the biological materials in the fluid by their dielectric potential. Each biological compound has a known dielectric constant. In the presence of an electrical field, the compound will migrate to the point were it is neutrally charged. Then the compound can be removed at its neutral point and thereby refined. The products at the point selected will all have the same dielectric constant and be the same biological material.

5.2 ACCELERATION REQUIREMENTS

In the presence of gravity, this type of separation would require a greater field strength. Samples would be separated but the resolution would not be as good. This on-orbit capability will provide the refining of drugs that could not be separated on Earth. The level at which the field strength becomes greater than the acceleration forces is currently believed to be around 1×10^{-4} g. This level has proven to be acceptable for the initial experiments on board the Shuttle. The larger systems envisioned will be trying to increase the resolution as well as the production. It does not appear that the increase in resolution will require a lessening of the gravity environment.

5.3 SELECTION CRITERION

The Continuous Flow Electrophoresis Facility was selected for this study as it represents the biological experiments from the acceleration, automation, and the crew activity points of view. This experiment has the longest run time (at continuous g levels) of any of the other biological experiments. It could be automated easily once the process is better defined. Crew requirements for sample changeout are the most severe of the biological experiments. This makes the Continuous Flow Electrophoresis Facility a good study candidate.

5.4 ASSUMPTIONS AND GUIDELINES

In addition to the common assumptions and guidelines defined in section 1.1, the following were considered for this facility:

- The sample is human kidney cells
- The characterization requires growth of the cells in a culture to determine the purity
- Samples are shipped freeze dried and mixed on-orbit
- Samples are refrigerated after processing.

6. DROPLET SPRAY BURNING FACILITY

6.1 DESCRIPTION

The Droplet Spray Burning Facility is a combustion chamber where a single drop or a matrix of droplets of fuel are free floated in the chamber and ignited. The absence of gravity will allow the droplet(s) to be free of gravity-induced convection during the burn. The oxygen required for combustion will be supplied by diffusion through the flame. This will allow the researchers to determine the role that the diffusion process plays in the total combustion of Earth-based systems, and the methods required to prevent and extinguish on-orbit fires.

6.2 ACCELERATION REQUIREMENTS

The g level requirement is 1×10^{-4} g during the actual burn. These burns typically take only a few seconds, although Space Station runs may be up to a minute.

6.3 SELECTION CRITERION

The Droplet Spray Burning Facility was selected because it represents the combustion science fields. The combustion experiments do not have long runs, but are typically very labor intensive. The run times of only a few seconds and the high labor requirement between runs make this experiment a good choice for the UNBIS study.

6.4 ASSUMPTIONS AND GUIDELINES

In addition to the common assumptions and guidelines defined in section 1.1, the following were considered for this facility:

- The fuel is toluene
- The combustion experiment is the study of flame interactions with a 3 x 3 x 3 matrix of droplets
- The facility is cleaned after each run.

7. FLOAT ZONE FACILITY

7.1 DESCRIPTION

The Float Zone Facility is similar to the MEPF furnace described under the Alloy Solidification Facility. However, in the Float Zone Facility, the sample is not encased in an ampoule. It is allowed to melt and resolidify in the furnace without the use of an ampoule to reduce the nucleations caused by the walls of the ampoules. The Float Zone technique does not melt the entire sample at once. The sample is secured at each end. There is a small zone near one end of the sample that is melted. This melted zone is of fixed length and is moved at a slow rate along the axial length of the sample until it is within a few centimeters of the end. The surface tension of the melt allows it to "hold" on to the solidified portion of the sample. As the floating zone moves, the impurities are forced out of the forming crystalline structure ahead of the solidification front.

7.2 ACCELERATION REQUIREMENTS

The Float Zone experiments are as sensitive to the acceleration environment as the materials described in the Alloy Solidification facility. The materials require a 1×10^{-6} g as a minimum. The matrix size, ion size, and particle size are such that the facility acceleration requirements are the same as the alloy experiments.

7.3 SELECTION CRITERION

The Float Zone Facility was selected for study under this contract because it is representative of the electronic materials discipline, and the float zone process is more labor intensive than the Bridgman techniques.

7.4 ASSUMPTIONS AND GUIDELINES

In addition to the common assumptions and guidelines defined in section 1.1, the following were considered for this facility:

- The sample is GaAs
- The translation rate is 1 cm per hour
- One sample is processed per run

- Sample characterization includes cutting the sample into wafers, viewing under a microscope, and operation of several probes to determine the quality of the material for the next run.

8. FLUID PHYSICS FACILITY

8.1 DESCRIPTION

The Fluid Physics Facility is used to perform a variety of fluids experiments. The facility contains optical equipment to measure fluid flows, sedimentation, and convection in the reduced gravity of the station. The experiments range from solution crystal growth, to applied science experiments, to the study of thermal bubble migration. Although a range of experiments are presented, the experiments all have some very basic requirements in common. They all are performed in a viscous fluid. The sample to be studied can either be suspended in the fluid, grown from materials saturated in the fluid, or be the actual fluid itself. The experiments can be attached to the facility or can be freely suspended inside the chamber. In the latter case, the fluids are monitored as the surface effects of the fluids are studied.

8.2 ACCELERATION REQUIREMENTS

The Fluid Physics Facility, as it supports a variety of experiments, has an acceleration level that is hard to identify with any one experiment. The freely suspended experiments are not very susceptible to the high frequency accelerations. However, lower low frequency accelerations allow for longer experiment runs without the sample contacting the wall. If a crystal is being grown from solution, the same logic detailed for any other crystal would apply. With a variety of acceleration requirements bounding the experiment set, an acceleration of 1×10^{-4} g is used.

8.3 SELECTION CRITERION

The facility that is used in this study is a candidate from the fluid group, and it will have the capability to freely suspend a sample in a chamber.

8.4 ASSUMPTIONS AND GUIDELINES

In addition to the common assumptions and guidelines defined in section 1.1, the following were considered for this facility:

- The experiment considered is a solution crystal growth experiment similar to the Fluids Experiment System (FES)

- The material is Triglycine Sulfate (TGS)
- The facility uses optical systems for the majority of the data gathered during the run.

9. LARGE BRIDGMAN FACILITY

9.1 DESCRIPTION

The Large Bridgman Facility is a directional solidification furnace like the one described in the Alloy Solidification Facility MEPF. The sample in this furnace is up to 10 cm in diameter and is to be pressurized to 80 atm. The larger samples are required for the large scale integrated circuit designer. The high operational pressures come from the fact that the HgCdTe materials to be grown have a +1200 °C melting point. At this temperature, the Mercury will be vaporized and come out of solution. Therefore, the system is pressurized to 80 atm, the vapor pressure of mercury at 1200 °C, to keep it in solution. After the solidification is complete the HgCdTe is stable at room temperatures and pressures.

9.2 ACCELERATION REQUIREMENTS

With the Large Bridgman Facility, the sample diameter of over 8 cm presents the station with the most restrictive acceleration requirement. The sample will require a 1×10^{-6} g environment for the low frequency levels. These experiments are preproduction activities. The actual production of bulk HgCdTe will not be accomplished in the USL.

9.3 SELECTION CRITERION

The Large Bridgman Facility was selected since it has the most restrictive acceleration requirement, requires long periods to grow the samples, and requires the movement of very heavy equipment to remove the sample on orbit. This heavy equipment is the pressure containment vessel for the facility. This vessel must be moved to service the furnace, remove samples, or to modify the hardware. This item represents the largest piece of hardware to be moved by the robot, not including the racks themselves.

9.4 ASSUMPTIONS AND GUIDELINES

In addition to the common assumptions and guidelines defined in section 1.1, the following were considered for this facility:

- The material is HgCdTe
- The sample must soak at temperature for 24 h to allow the melt to become homogeneous
- The translation rate is 30 cm per hour
- Characterization includes cutting, viewing, x-ray, probing, and Fourier Transform Infrared Spectrometer (FTIR) analysis.

10. PROTEIN CRYSTAL GROWTH FACILITY

10.1 DESCRIPTION

The Protein Crystal Growth Facility is a chamber, with a controlled environment, used to allow protein crystals to form. Protein crystals are grown from vapors or solutions. Typically, the vapor method is used. In this method, a concentrated protein is placed near a solution which contains a high salt concentration. The salt concentration then draws the free water vapor from the concentrated solution. This supersaturates the protein solution. The supersaturated solution then nucleates and a crystal is formed. The crystal continues to grow until the solution is no longer supersaturated. The environment of the facility is conditioned to provide the solutions with the ideal temperature for the nucleation to take place. The typical protein crystal is 1 to 3 mm when grown on Earth. Results from the Shuttle experiments show that the crystals can be grown to much larger sizes. The crystals are of no use themselves; however, when bombarded with x-rays, they reveal the structure of the proteins. This process of bombarding the crystal, called x-ray diffraction, gives the relative positions of the elements in the protein molecule. With this information, the user can design drugs that function the same as the protein or combat the protein. This will be the first step in the era of drug designers. To date, the drugs are developed based on theoretical data. The use of protein crystals to physically show the drug developers how to build their drugs would remove the guesswork.

10.2 ACCELERATION REQUIREMENTS

The protein crystals are very fragile. They have been described as pickup sticks held together in a viscous fluid like honey. They have no real structure, and the slightest bump will destroy them. The experience of the Shuttle flights shows that they may not even be able to withstand the re-entry loads. These samples will be x-rayed on orbit to increase the effective throughput of the facility. The process of moving a grown crystal from the growth chamber to the x-ray diffractometer is a difficult task. The sample will require the mover to not exceed the 1×10^{-4} g level or the sample could be lost.

10.3 SELECTION CRITERION

Up to 1000 crystals are grown in one facility run. There are several reasons for this large number of crystals per run. First, the x-ray system will destroy the sample after a few minutes of exposure. The x-ray pattern requires hours of exposure time and the crystals only last for minutes. This implies that, out of 1,000 crystals grown, hopefully one diffraction pattern will be obtained. Also, the protein crystals do not grow consistently. Therefore, for any given run, 1 out of 10 crystals do not nucleate on themselves. Only the crystals that nucleate on themselves are usable. This is because these have the correct single-crystal shape and planes required for the diffraction analysis. Therefore, of the 1,000 grown, only about 100 are usable.

These limitations on the crystal structure, the heavy crew involvement, the precise handling requirements, and the x-ray environment all lend themselves to a robotic system to support the protein crystal facility. The movement of the samples from the facility to the x-ray system will require a steady handed crewman or a robot. For these reasons this facility was selected for this study.

10.4 ASSUMPTIONS AND GUIDELINES

In addition to the common assumptions and guidelines defined in section 1.1, the following were considered for this facility:

- The sample is Interferon grown by the vapor transport method
- The growth time is 10 days
- The finished crystals are viewed under a microscope for determining those suitable for x-ray diffractions
- X-ray diffraction analysis of the sample is completed before the next run is started.

11. VAPOR CRYSTAL GROWTH FACILITY

11.1 DESCRIPTION

The Vapor Crystal Growth Facility studies the growth of crystals from a vapor. The seed crystal is placed in one end of an ampoule, and the unprocessed material is placed in the other. The material is heated to just under the melting point. The seed is cooled to several degrees below the solidification point. The vapor pressure of the materials near the melting point forces the material to be driven out of the bulk material and be condensed onto the cooler seed. With the absence of gravity, the transfer from the hot side to the cool is driven only by diffusion forces, not the convection that would disrupt the reformation on the seed.

11.2 ACCELERATION REQUIREMENTS

This process is a diffusion controlled experiment, as is the PCG experiment. The Vapor Crystal Growth Facility, however, requires 1×10^{-5} g during the growth of the crystal.

11.3 SELECTION CRITERION

The Vapor Crystal facility is more sensitive than the PCG experiments during the growth phase. For this reason, the Vapor Crystal Facility was added to the study.

11.4 ASSUMPTIONS AND GUIDELINES

In addition to the common assumptions and guidelines defined in section 1.1, the following were considered for this facility:

- Sample is HgI
- Only one furnace module was used
- Mass included only the single rack of equipment required to support one furnace module.

APPENDIX B

ROBOTIC MICROSTEPPING REPORT

October 1989

1. ROBOTIC MICROSTEPPING REPORT

Detailed descriptions, complete sets of data, and results of this microstepping test appear in the Interim Report, User Needs, Benefits, and Integration of Robotic Systems in a Space Station Laboratory, NASA CR182261.

A series of tests were performed to characterize a microstepping motor using an industrial robot (Intelledex Model 660). By rotating the base of the robot at one of several speed settings, important parameters such as acceleration, deceleration, and velocity are derived. Two different sets of displacements were measured to achieve this objective.

- Major displacement - a relatively large displacement (0.05 rad). This displacement could be viewed as an accumulation of microsteps. It is easier to observe the ramp of an acceleration, deceleration, and slew speed phases (see Figures B-1 and B-3).
- Minor displacement - a relatively small displacement (0.0002 rad). Results generated from the minor displacement measurements would represent an approximate range of the accelerations and decelerations which is achievable using the current industrial robot technology.

The task was performed as follows (see Figure B-2):

- Two Linear Variable Differential Transformers (LVDTs) are chosen. One is calibrated to measure a minor displacement and the second one to measure a major displacement.
- The 660 is programmed to rotate its base at a predetermined speed.
- As the base rotates, the displacement pulse is captured with the 7D20 Digitizer/Oscilloscope. The digitized pulse is sent to the 4041 System Controller via a General Purpose Interface Bus (GPIB).
- The raw displacement pulse is processed to remove digitizing (round-off) errors. The processed data is then differentiated to derive the velocity profile. A second derivative of the processed data results in an acceleration profile (see Figures B-3 and B-4).

From the data acquired, the following are observed.

- The minimal movement of the base motor is defined to be 0.0003 deg (0.000047746 rad). However, because of an encoder with a lesser resolution (0.00178 deg), the robot controller did not respond to a microstep increment. Based on this observation, a

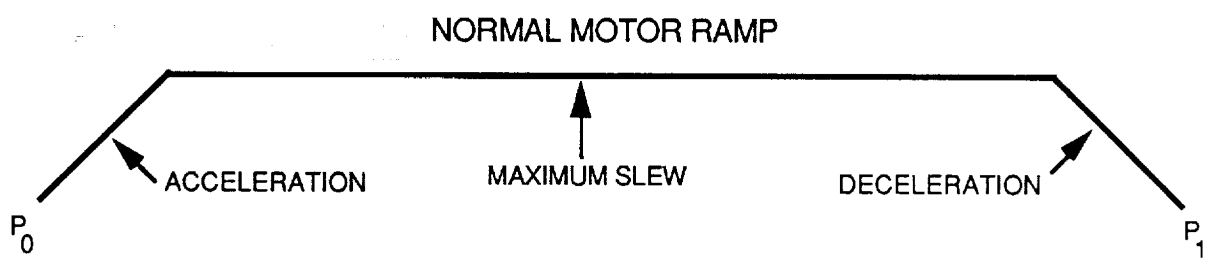


FIGURE B-1. ACCELERATION, DECELERATION (RAMP) AND CONSTANT VELOCITY PERIOD (SLEW) FOR TYPICAL ROBOT DISPLACEMENT

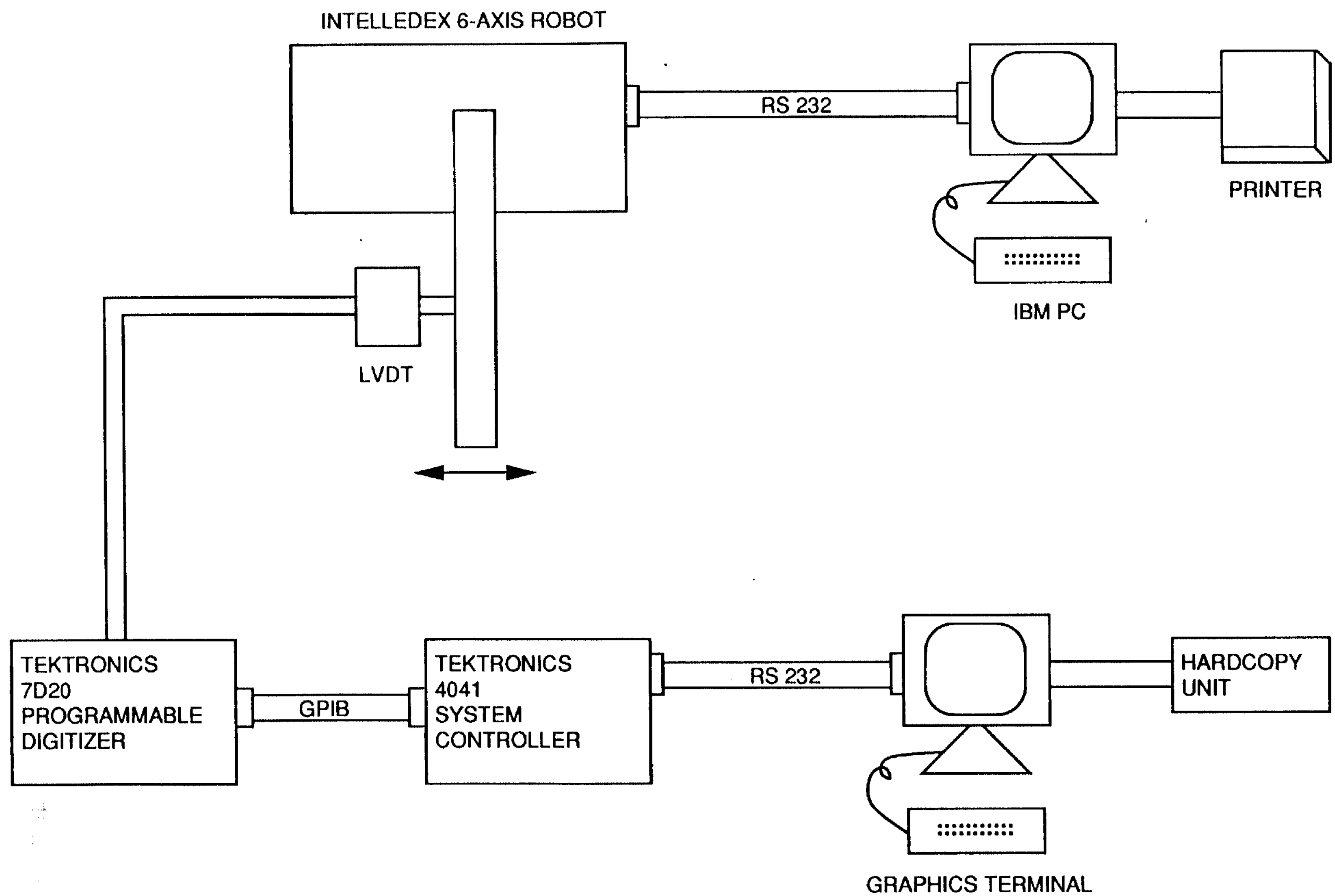
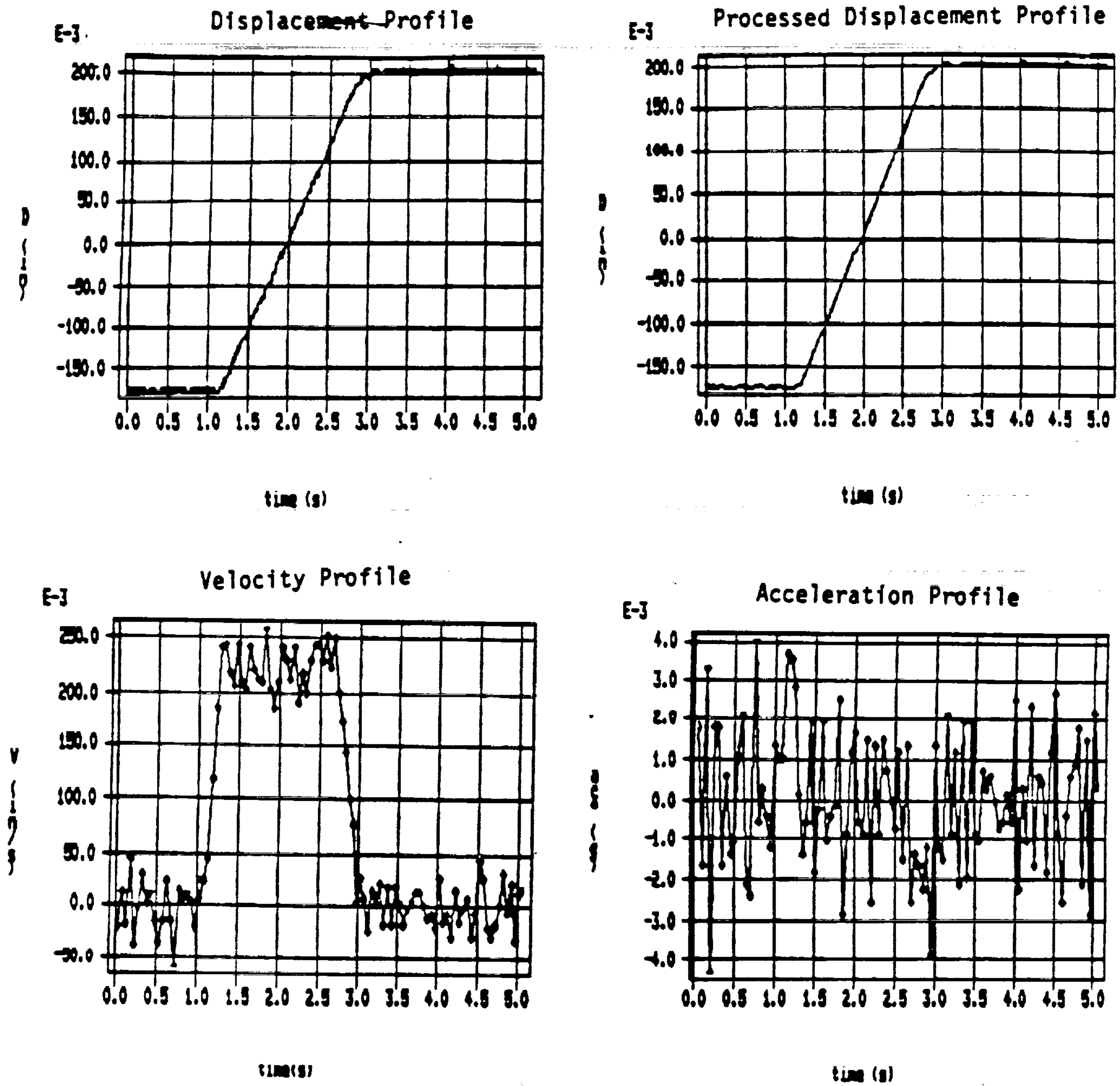


FIGURE B-2. SETUP FOR MANIPULATOR MICROSTEPPING EVALUATION minor displacement case was used to represent the microstepping of the base motor.

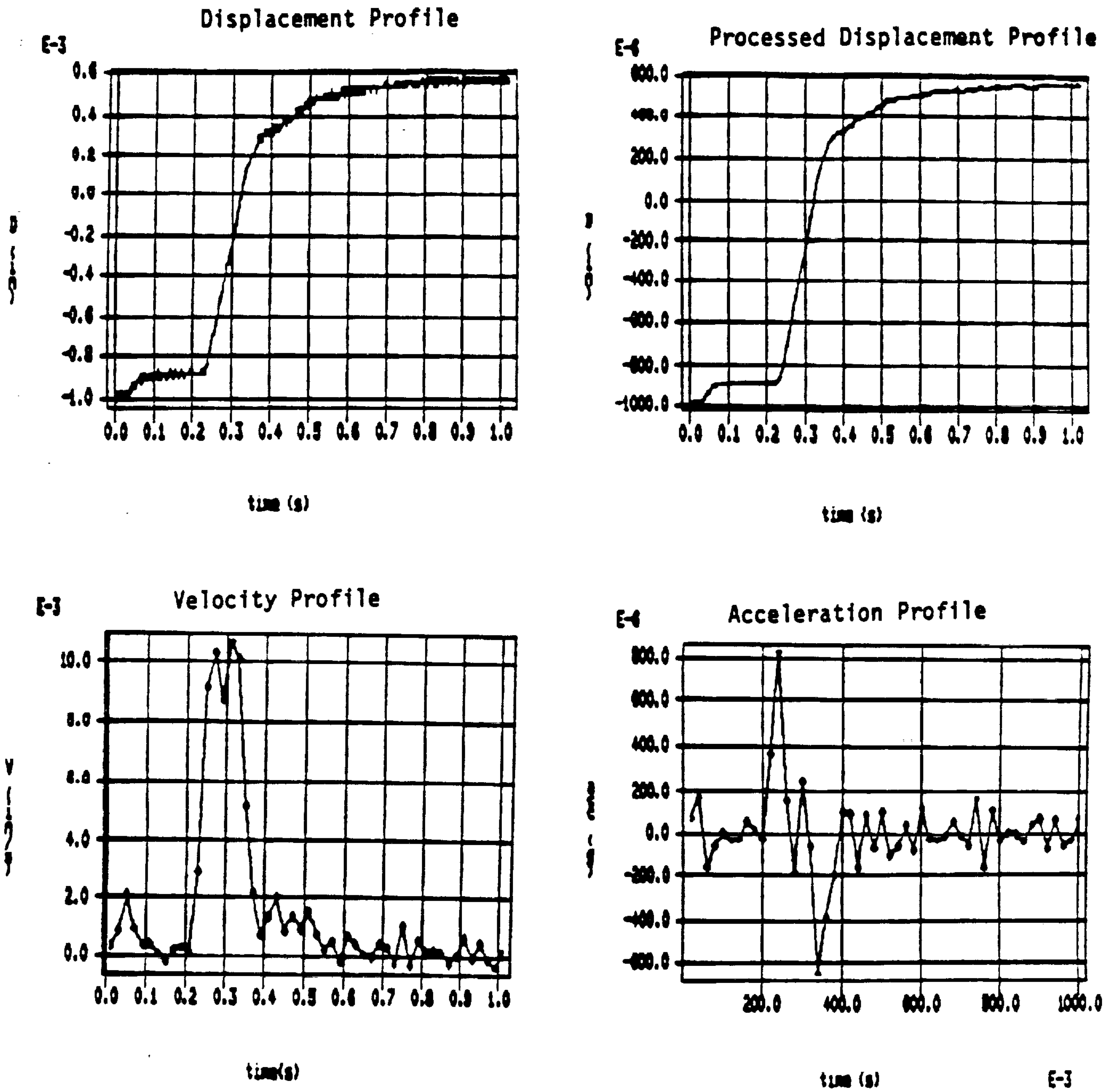
- Figure B-3, major displacement case, delineates a clear ramp of accel/decel and the slew phase of a major displacement. It is observed that approximately (+4, -4) milli-g of acceleration is exhibited.
- Figure B-4, minor displacement case, displays a peak acceleration of +0.8 milli-g and -0.8 milli-g. There was a reduction in the magnitude of the acceleration by a factor of 5 comparing to the major displacement case. There is a noticeable reduction in the magnitude of the accel/decel as the amount of total displacement decreases.

It was concluded that an industrial stepper-motor robot displacement was achieved at less than 1 milli-g acceleration. Although not compatible with experiments/process microgravity requirements, it should not be expected to be compatible. This level of accel/decel range indicates the potential applicability of microstepping techniques and path control to a reactionless microgravity manipulator.



IMOVE0	-0.05
CASE	I
SPEED	(0, 0, 0)
MAXSPEED	0

FIGURE B-3. MAJOR DISPLACEMENT PROFILES



IMOVE0 -0.0002
CASE I
SPEED (0, 0, 0)
MAXSPEED 0

FIGURE B-4. MINOR DISPLACEMENT PROFILES

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